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FEASIBILITY STUDY OF ELECTROMAGNETIC SUBSURFACE PROFILING

Rexford M. Morey, et al

Geophysical Survey Systems, Incorporated

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Feasibility Study of Electromagnetic Subsurface Profiling

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A study was made of a unique radar system which produces a continuous profile of subsurface conditions showing depth and location of geological formations and buried utilities. Information is obtained by sending electromagnetic pulses into the earth and then receiving the reflected pulses from interfaces and objects. The unit travels at 3 mph, and can detect interfaces directly below it to depths of 10 feet in clay and 25 feet in sand. Depth of penetration is governed by conductivity and dielectric constant. Water content influences these soil parameters; an increase in water content decreases penetration. The penetrability of the soil determines the maximum depth at which pipes can be detected. A break in the pipe can be detected by the saturated soil around the break. Limits of penetration have not been reached; work is being done to determine empirical standards of system performance on a wide variety of soils. Since better information yields better cost estimates for designing sewage collection systems, the advantages of the radar system are apparent. (EPA abstract)

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FEASIBILITY STUDY OF ELECTROMAGNETIC SUBSURFACE PROFILING

By

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ABSTRACT

A study was made of a unique radar system which produces a continuous profile of subsurface conditions showing depth and location of geological formations and buried utilities. Information is obtained by sending electromagnetic pulses into the earth and then receiving the reflected pulses from interfaces and objects. The unit travels at 3 mph, and can detect interfaces directly below it to depths of 10 feet in clay and 25 feet in sand. Depth of penetration is governed by conductivity and dielectric constant. Water content influences these soil parameters; an increase in water content decreases penetration. The penetrability of the soil determines the maximum depth at which pipes can be detected. A break in the pipe can be detected by the saturated soil around the break. Limits of penetration have not been reached; work is being done to determine empirical standards of system performance on a wide variety of soils. Since better information yields better cost estimates for designing sewage collection systems, the advantages of the radar system are apparent.

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SECTION I

CONCLUSIONS

1. At present, engineers and municipalities have no systematic, comprehensive method of obtaining continuous underground information to pin-point the location of bedrock and utilities. The cost of laying new sewer pipe is approximately $100,000/mile; it soars when extensive bedrock, gas-pipes, telephone wires, etc., are encountered and have to be avoided or repaired if damaged. A method to provide better subsurface information would solve the major problem of estimating the cost of installing new sewer pipe. Another facet of the same problem is that there is no method of locating "lost" or broken pipe in an extant sewer system. Public Works crews must dig and refill holes in an inefficient quest of faulty water and sewer lines.

2. Present methods of determining the quantity of bedrock consist of borings and seismic soundings. Borings do not provide enough information at a reasonable cost, and seismic soundings do not work well at the depths where most utilities are located. When they even exist, maps and plans showing the location of buried utilities depend upon surface references that may have been moved or obliterated during subsequent construction.

3. A radar system developed by Geophysical Survey Systems, Inc., presents a non-destructive method of profiling the earth. It transmits an electromagnetic pulse into the earth, and receives and analyzes return pulses which have been reflected from interfaces. The depth of the medium can be determined from the reflected pulse. It is also possible in theory to identify materials from this pulse. Depth of penetration of the signal is governed by the conductivity and the dielectric constant of the medium. As the conductivity increases, attenuation of the signal increases; and therefore, penetration by the pulse decreases. The effect of water content of four samples was measured in the laboratory. The percent saturation with water in a silty sand sample was increased from 2% to 20% and the effective penetration was reduced by 46%.

4. Initially, maximum penetration of the pulse through sand in field studies was 25-feet; penetration through varved clay was 5-feet. Tests conducted after this program was completed indicate penetration limits have been expanded to 60-feet through sand, and 10-feet through varved clay.

   Laboratory work with metal and non-metal pipes indicates that metal pipes can be located readily at these same depths. If the non-metal pipe is filled, it is as easily detected as the metal pipes at the same depths through the same materials.

   The system detected the saturated zone of soil around the break in a transite pipe buried 3 feet-8 inches in a soil composed of 98% sand, and 2% silt.

5. The system at present is utilized in soil and bedrock surveys, and underground utility mapping. Soil and bedrock surveys consist of a visual inspection by a geologist, an ESP survey along the proposed trench route, an initial interpretation of the data to direct a limited boring program for material identification and to calibrate the data,

and a final interpretation and report. Underground utility mapping includes gridding the street or intersection on a 10-foot grid pattern, taking the ESP survey along the grid lines, logging all visible indications such as manholes and gates, checking all available utility maps, and plotting all this information plus ESP survey results on a drawing.

6. The system is presently used commercially for subsurface investigations in the New England area. The main application of the impulse radar system is in the location and identification of buried or submerged materials, either man-made or natural. Its unique abilities make it an invaluable tool in any field which requires probing the earth.

SECTION II

RECOMMENDATIONS

This project was limited to gathering basic information of system performance on soils, bedrock, and underground utilities. Limited laboratory and field studies were performed under ideal conditions. Field tests should be continued in a wide variety of soils to determine the system's capacities. Due to modifications and improvements of the antenna, depths of penetration in all media are constantly expanding; limits have not yet been reached. Although it is known that the radar will penetrate certain materials, the degree of influence of characteristics such as the number of soil layers, or the water content should be established. Resistivity measurements are being made in the field with the radar to determine empirical guidelines which would then serve to evaluate the ability of the system to perform under different circumstances in various locations. Laboratory analysis of soils should be continued to determine the correlation between electrical parameters of a medium and penetration limits of the system for a particular medium and for combinations of materials. An in-depth investigation of how materials affect broadband video pulses must be performed. In order to enhance data presentation and to facilitate interpretation of the ESP data, it is recommended that computer processing of the data be developed. Finally, data handling should be automated as much as possible.

It is now necessary to use borings in conjunction with the radar system for material identification and system calibration. It is recommended that this need for borings be eliminated. Further investigations should be conducted to prove that media can be identified by knowing the incident and reflected video pulses. These investigations should study the pulse characteristics, computer analysis, and development of the theory associated with the transmission of the pulse through a multi-layer medium.

A full-scale demonstration is recommended. The costs and problems encountered by one municipality building a collection system by means of standard subsurface investigation techniques would be monitored. ESP surveys would be performed for another cooperating municipality having essentially equivalent problems. Final construction costs for both municipalities would be compared.

SECTION III

INTRODUCTION

The present sewage collection system in the United States represents a tremendous unseen investment, and the cost of putting additional sewer pipe into service will increase this investment to about $82 billion by 1980. The U. S. Department of Commerce predicted that 2.94 billion linear feet of residential sewer pipe would be in the ground by 1970. This represents an investment of $53 billion. By 1980, the prediction is that 3.73 billion linear feet of residential sewer pipe would be in service to handle the flow from 178 million residents. It becomes economically important to have a thorough understanding of subsurface conditons for the efficient design of subsurface sewage collection systems. Ignorance of detailed subsurface conditions is the major problem in planning and estimating the cost of installing sewer pipe. These costs are primarily affected by the geology and the buried utilities along the excavation path.

Presently available methods of mapping the subsurface conditions along a proposed trenching route are not adequate in most cases. For excavation work, the material of primary interest is bedrock, since the result of errors in estimating the quantity of bedrock can be very expensive. The most common subsurface investigation technique is boring a hole in the ground. Rods of various types may be either hammered or drilled into the ground. The operator counts the number of hammer blows to determine the density of the material. If drilling is used, the material is brought to the surface for evaluation. In both methods soil samples are sometimes taken for laboratory analysis. Borings give information only at the probed points and do not differentiate between bedrock and large boulders. Depending upon the nature of the investigation, holes are placed every 50 or 100 feet and occasionally as far apart as every 300 feet. Interpolations of data are then made between these holes to form estimated profiles of subsurface conditions.

Seismic (sound) profiling is a relatively deep acoustical sounding technique that does not work well at shallow depths of 10 to 20 feet because of the very short propagation times involved. Sound waves generated at the surface of the ground are reflected from various layers in the subsurface and are detected by geophones stuck in the ground. The geophones convert the sound into an electrical signal for recording. The initial seismic energy is generated by explosives buried in the ground, or by striking the ground with a sledge hammer, or by inducing vibrations in the ground with a mechanical device. Continuous subsurface profiles cannot be developed by land seismic surveying.

The location and identification of underground utilities, such as water, gas, and telephone, is necessary for the design and installation of new sewer collection systems. Presently, this information is retained on maps and plans maintained by the various utility companies and the cities and towns. In many cases the plans do not exist or are inadequate for actually locating the utility in the street.

Geophysical Survey Systems, Inc. has developed a unique radar system for shallow subsurface exploration. This system is called Electromagnetic Subsurface Profiling (ESP). The system produces a continuous profile of subsurface conditions showing the depth and location of geological formations and buried utilities. This report demonstrates and evaluates the ESP system's ability to detect difficult excavation conditions that affect

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sewer construction costs. The report is three-fold in nature. First, a brief description of the theory and operation of the ESP system is presented. Second, subsurface geology as it affects the characteristics and capabilities of the ESP system is discussed. Finally, buried utility location and identification capabilities of the ESP system are outlined.

Geophysical Survey Systems, Inc. obtains subsurface information by sending electromagnetic waves into the earth from an antenna moving across the ground. As the energy penetrates the ground it is reflected in part by various geological interfaces and objects in the ground. These reflections are picked up by the antenna and detected by a sensitive receiver for recording on magnetic tape. The magnetic tapes on which the data are stored are then processed and the data are converted into a graph. These graphs are one of the main tools employed by the Company's geophysicists and geologists for determining subsurface conditions and for producing continuous subsurface profiles.

SECTION IV

DESCRIPTION OF THE ESP SYSTEM

This section will describe the principles, theory, and operation procedures of the Electromagnetic Subsurface Profiling (ESP) system.

The ESP System is a broadband video pulse radar. This video pulse radar system emits a pulse that is approximately Gaussian in shape (see Figure 1a). It is possible to express this time domain video pulse through its fourier transform as a frequency spectrum (see Figure 1b). The reflection of each of the spectral components and hence the video pulse is determined by the dielectric constant and conductivity of the medium from which it is reflected. This is because the reflected pulse must satisfy the boundary conditions at each interface. These boundary conditions are derived from Maxwell's equations (Ref. 1).

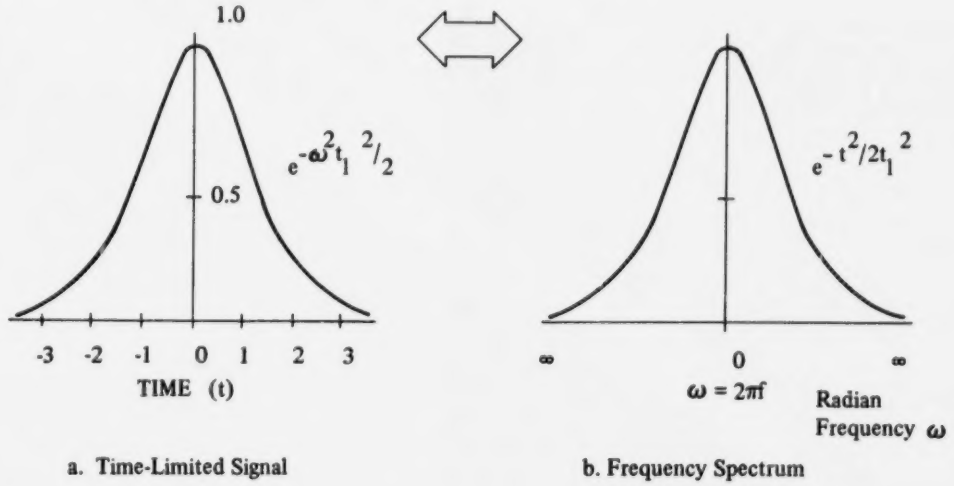

Figure 1. Frequency Spectrum of a Time-Limited Signal (Gaussian)

If the video pulse passes through multiple media it is partially reflected and partially transmitted at each interface (see Figure 2). It is the reflected pulse that the radar system developed by Geophysical Survey Systems, Inc. detects, records, and analyzes.

Video pulse propagation through naturally occurring media is a complicated phenomenon. Physical and chemical properties of a medium affect the dielectric constant and conductivity. The dielectric constant and conductivity in turn influence video pulse shape and propagation. It is with these two parameters that the theory and experimentation are concerned. The dielectric constant determines the velocity at which the video pulse travels through the medium. If the velocity and time of travel are known, the thickness of the

material can be determined. The conductivity of a medium causes heat loss of energy in the pulse and determines the attenuation or loss of energy as the pulse propagates through the medium. These two parameters depend on the density and moisture content of the medium. Section VI illustrates how these parameters vary for different soils and moisture content.

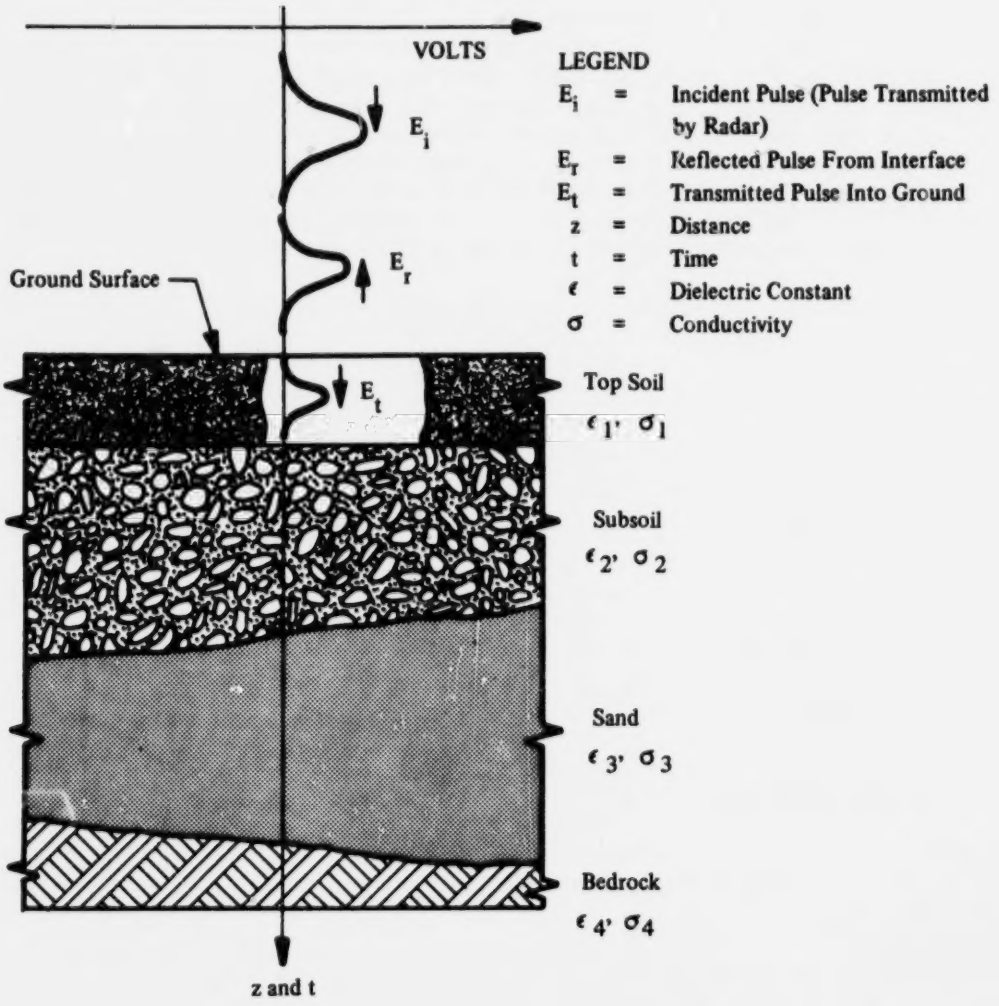

Figure 2. Example of Subsurface Profile

The time-limited signal (video pulse) shown in Figure 1a is assumed to be Gaussian in form, which is close to the form it has in practice since there is a finite rise and decay time. The Gaussian pulse f(t) is represented mathematically by the relation:

$$f(t) = e^{-t^2/2t_1^2} \tag{1}$$

where t_1 is the width of the pulse. The pulse given by (1) can be decomposed into a frequency spectrum F (ω) where

$$F(\omega) = \int_{-\infty}^{\infty} f(t) e^{j\omega t} dt \tag{2}$$

If f(t) is given by (1), then the corresponding spectrum F (ω) can be found from (2)

$$F(\omega) = e^{\omega^2 t_1^2/2} \tag{3}$$

A narrow time or video pulse is associated with wide frequency spectrum. For example, if the time pulse is in the order of one nanosecond (10^{-9} seconds) in half width, then the frequency spectrum extends from zero to about 350 MHz. The response R (ω) of a particular material to a single frequency can be calculated. The actual reflected signal in the time domain is then obtained by superposition. Thus the time response r (t) which corresponds to R (ω) is

$$r(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} R(\omega)\ F(\omega)\, e^{-j\omega t}\, d\omega \tag{4}$$

where F (ω) is the frequency spectrum of the pulse. The relevant quantity for subsurface exploration is the coefficient of reflection R (ω). For a two-layered medium it is

$$R = \frac{k_2 - k_1}{k_2 + k_1} \tag{5}$$

$$k_1^2 = \omega^2 \epsilon_1 - j\omega\mu_1\sigma_1 \qquad k_2^2 = \omega^2 y_2 \epsilon_2 - j\omega\mu_2\sigma_2 \tag{6}$$

where

μ = magnetic constant
ϵ = electric (or dielectric) constant
σ = conductivity

Equation (5) shows that a signal at a single frequency gives rise to a reflected signal that is proportional to the difference in the electrical properties of the materials. Since the propagation factors given by (6) are frequency dependent, it appears possible to find some frequencies which give rise to large reflections, and others for which there is a negligible returned signal. The ESP System takes advantage to this relationship by producing a pulse composed of a wide frequency spectrum from which it is usually possible to produce an appreciable reflection.

The depth of penetration of the signal is not only dependent of the strength of the signal, but is also dependent of the frequency content of the pulse. For example, the properties of the earth generally allow the low frequency components to propagate to the greatest depths. However, it is the higher frequency components that give rise to the resolution or the ability to discriminate between closely spaced interfaces and targets.

The ESP System is composed of a video pulse transmitter, a receiver, an antenna, a tape recorder, a graphic recorder, and special control electronics as depicted in Figure 3. The present unit is packaged in the rear of a four-wheel drive Chevrolet "Carryall" van (see Figures 4 and 5). The essence of the ESP subsurface investigation method is the analysis of **recorded reflections of radar signals directed into the ground.**

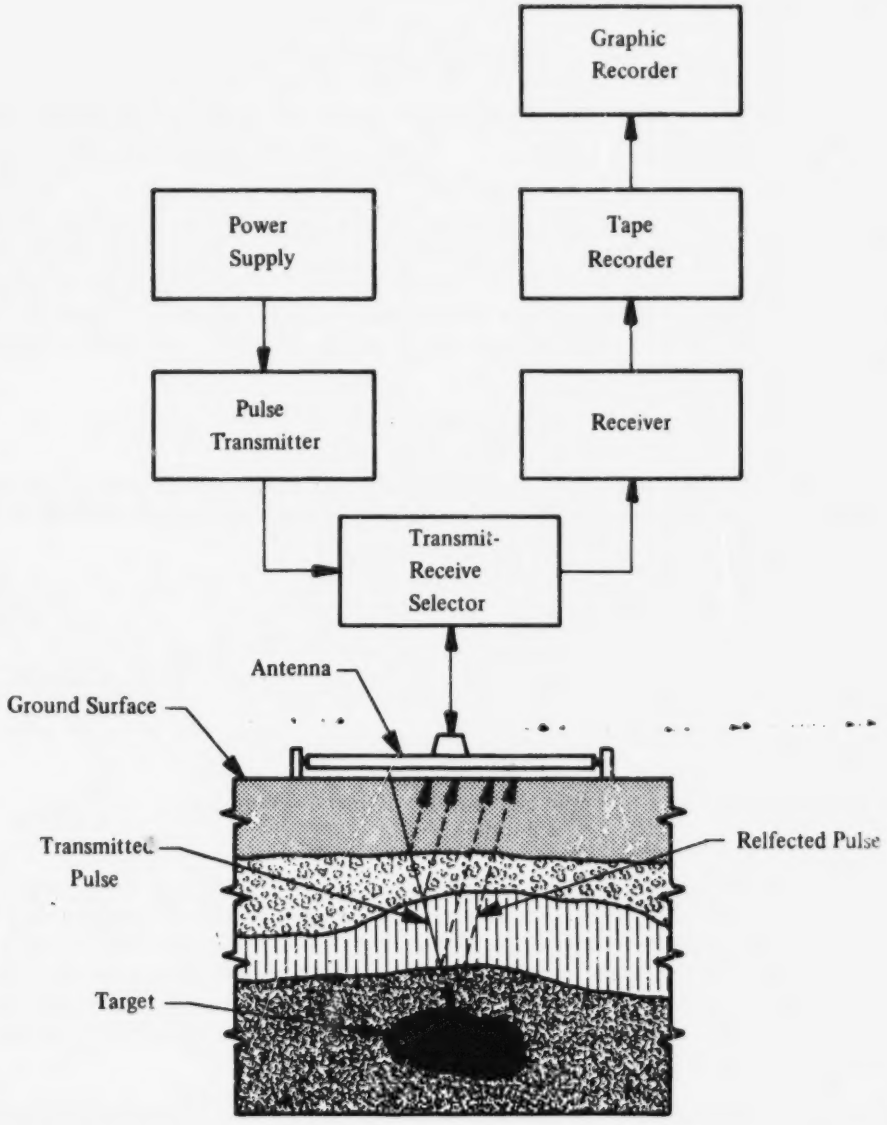

Figure 3. Block Diagram of ESP System

Figure 4. ESP System in Operation

Figure 5. Interior of Truck

Once an area for subsurface investigation has been established, the lightweight antenna unit is towed over the ground by truck or by hand (see Figures 6 and 7). The antenna transmits a radar pulse into the ground every three inches of travel. A portion of the radar pulse is reflected from the interfaces of soil, rock and other objects and received by the antenna. Radar reflections from the interfaces are governed by the differential in the dielectric constant and conductivity of the materials. A cable connects the antenna with receiving and recording instruments in the truck. The radar pulses are displayed in real time on a screen and are recorded on magnetic tape. By recording a signal return every three inches, a continuous profile is developed showing utilities and subsurface strata.

Figure 6. Antenna Being Towed by Hand

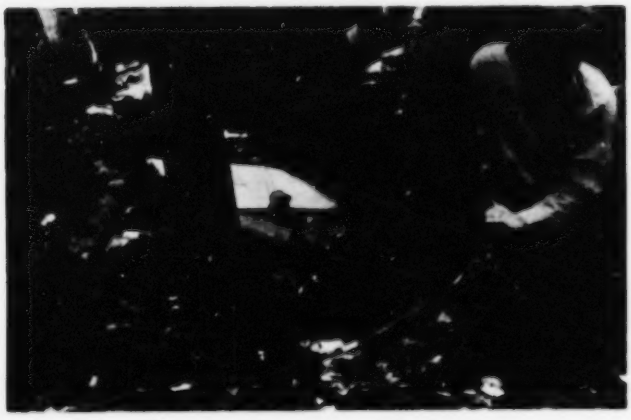

Figure 7. Antenna Unit Operating in Rough Terrain

A typical ESP graph is shown in Figure 8. Interpretation of these graphs requires a great deal of skill and experience; however, a few pointers on interpretation will be given. The graphic presentation of a vertical cross-section of earth is called a "profile". The "profile" has been produced by printing high signal levels in black and no signal white. Intermediate signals are in the gray range. The surface of the ground is the top horizontal line. The horizontal scale in feet is dependent upon the speed of the antenna across the ground. The horizontal scale in the example is approximately 40-feet per inch. The vertical scale is a time scale, which is converted into a depth scale with a knowledge of the velocity of propagation in the particular material. The main feature of the data is the display of dark bands which extend throughout the profile at varying depths. Note that these dark bands are displayed in groups of three closely related bands. Each group of three banded lines is the reflection from an interface between two materials. The triple band is a characteristic of the ESP System and is caused by oscillations in the reflection of the pulse. This oscillation or banding limits the ability of the system to discriminate closely spaced interfaces. In the sample of data shown, for example, the total span of the three banded signal is 2-feet. This means that as the spacing between two interfaces approaches 2-feet, the reflections from these interfaces will begin to superimpose. The lower interface will not be completely masked since portions of the oscillations will show up in the data. However, it will be difficult to locate the actual depth of the second interface.

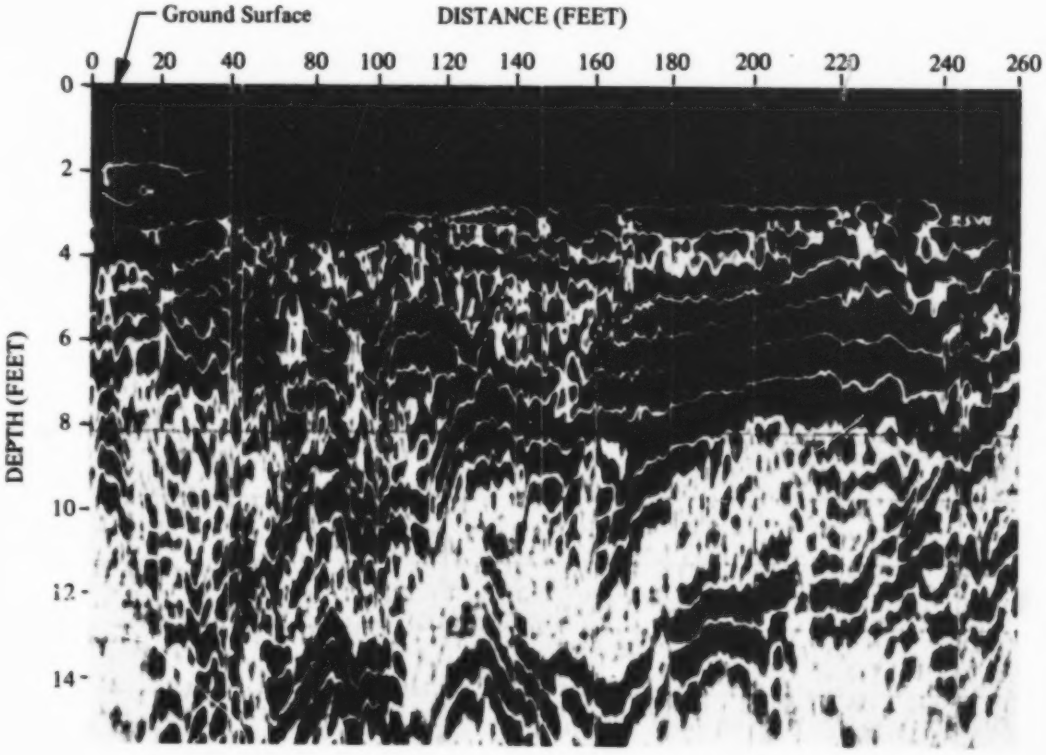

Figure 8. Typical ESP Graph

Note also in Figure 8 that there are 4 dark bands just beneath the surface running the length of the data. These bands are caused by the reflections from the surface and interfaces immediately below the surface. They cause difficulty in tracing interfaces up to the surface; however, there is information contained in this zone. Strong reflections from pipes can be picked out of this zone easily, and discontinuities in the surface which may be caused by trenching or changes from one surface material to another are easily identified.

SECTION V

OBJECTIVES

Geophysical Survey Systems, Inc. (GSS) has been contracted by the Environmental Protection Agency (EPA) to provide the necessary personnel, materials, and facilities to demonstrate and evaluate GSS's unique radar geophysical measurement system for shallow subsurface exploration. GSS, Inc. provided and maintained, at its own expense, the Electromagnetic Subsurface Profiling System.

The objectives of this evaluation are:

1. To determine the signature or picture characteristics of the geological formations most frequently enountered in sewage collection system construction, and the relevant anomalies such as buried pipe, cables, difficult excavation conditions, etc., that affect sewer construction cost.
2. To determine the eccentricity possibilities of the measurement system; that is, to determine the possible effects of the shape and/or composition (absorption/reflection) of a buried material on signature curves and other elements as encountered in the course of the demonstration. The intent is to outline possible causes of departure and degree of departure from the fundamental signature curves.
3. To make a "first-cut" estimate of the numbers and kinds of interfaces which can be identified at one time before the signature curves overlap.
4. To establish the depth limitations of the measurement system under common geological conditions and with the most frequently encountered obstacles.
5. To compare the curves of broken or crushed sewer pipe with intact pipe with all other variables remaining constant.
6. To develop a utilitarian method of logging and recording results for use by field crews. The intent is to have a well thought out method and technique for which the system can be used in a full-scale demonstration. As part of this task, possible sites for full-scale demonstration project are suggested.

To meet these objectives, the project is divided into two major parts; (1) geological considerations and (2) an underground pipe and utility study. Laboratory measurements and field measurements are performed during the investigation of each of the two parts of the project.

SECTION VI

GEOLOGICAL CONSIDERATIONS

Of the geological formations encountered in the construction of sewage collection systems, the one presenting the most difficult excavation conditions is bedrock. In order to study bedrock with the ESP System, an associated study of the overburden must be included. In addition, the most important part of any study of buried pipes is a study of the medium in which the pipe is buried. Therefore, most of the data gathered in this section concern the soil components of the overburden.

To evaluate the ESP System and its ability to detect geological phenomenon and other subsurface conditions, it is necessary to determine the radiation characteristics of the antenna and to determine the response of the system to various soil materials and conditions. To accomplish this end, the study program was organized as follows:

1. Measurements of the antenna's field of view were made in a controlled situation. The results of this experiment provide an insight into the printout characteristics, or signature, of various underground targets, the effects that side targets can have on the recorded information, and the limitations on the system's ability to detect sloping surfaces.
2. Data were collected in various natural situations using the ESP System. These data, when printed out and studied, provide information regarding the capabilities and limitations of the system. They also provide signature information for various geological phenomena.
3. Soil samples were collected from all the sites investigated with the ESP System. These samples were analyzed in the laboratory to determine soil properties that could affect system operation. In addition to grain size and moisture content determinations, electrical characteristics of the samples were measured under naturalistic conditions. Water content was varied in some samples to determine the effect of water on system characteristics.

During the initial phases of the project, a test pit was constructed (see Figure 9) for making laboratory measurements. This pit was originally used to reconstruct various soil and geological situations. This approach to geological studies became impractical. More time was spent filling the pit or changing the material in the pit than in collecting data. In addition, the situations created were artificial and the data collected not likely to bear any relationship to field conditions. It was decided to use the test pit as a laboratory standard or control and to use it extensively in the buried pipe studies.

Antenna pattern measurements were taken in order to understand the reflections received by the system from broad irregular surfaces such as those encountered in natural geological situations. A 12-inch diameter steel pipe installed in the test pit was selected as the target for these measurements, since the pipe presents a long, narrow, polarized reflector to the antenna. The strength of the reflected signal from the pipe for various beam angles was recorded along a line normal to the target axis (see Figure 10). These measurements were taken for both the front-to-back plane and the side-to-side plane. The results of these measurements are shown in Figures 11 and 12. These patterns differ from the conventional free-space radiation patterns of an antenna. They are a measure of the

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two-way reflection sensitivity, or the field of view, of the antenna. This information is essential in determining how normal printout signatures can be affected by changes in reflector surface shape or slope, and how the signatures are affected by subsurface perturbations within the field of view.

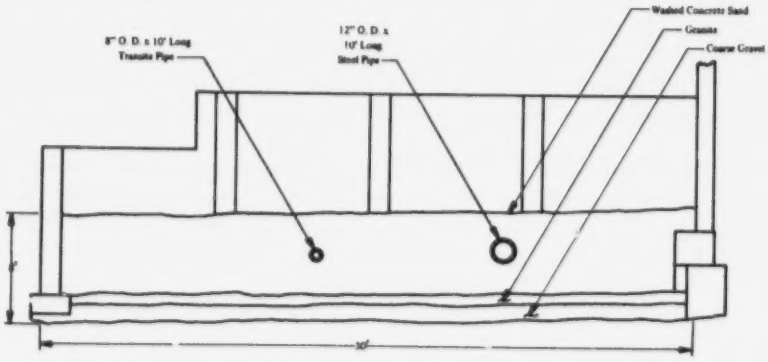


Figure 9. Test Pit

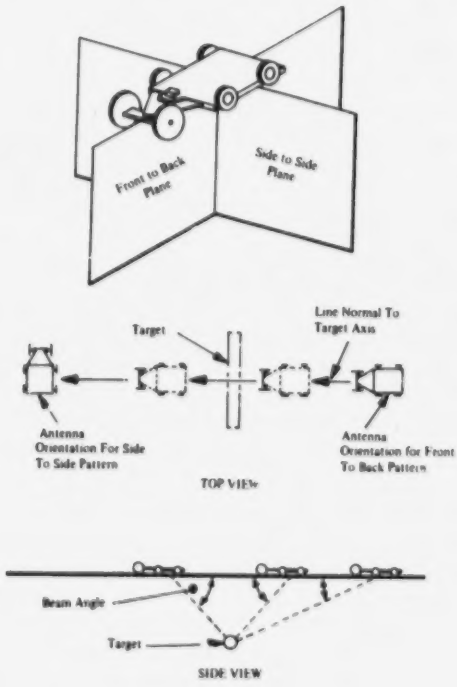


Figure 10. Set-Up for Antenna Pattern Measurements

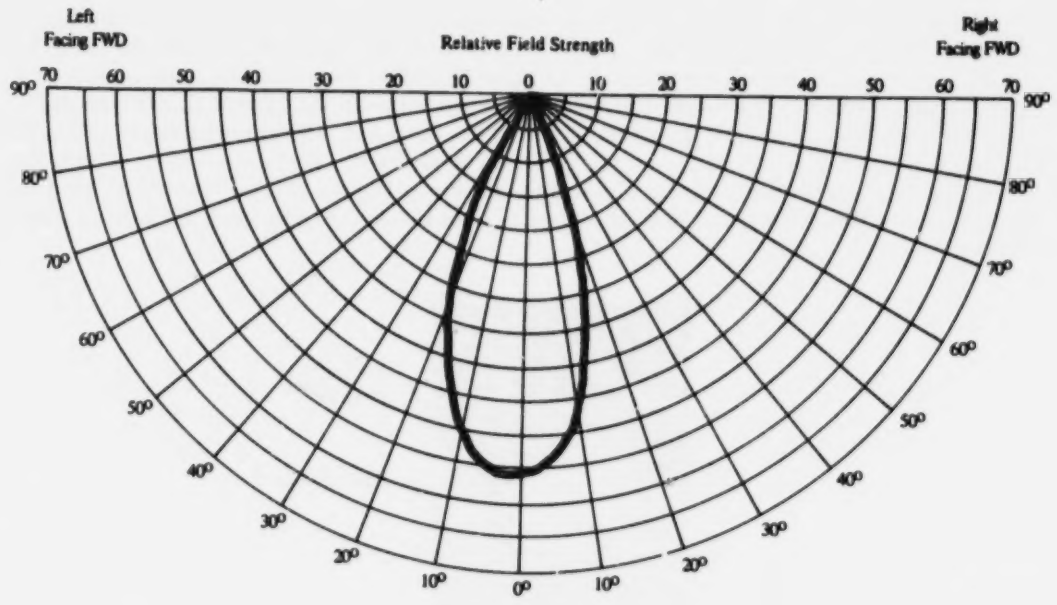


Figure 11. Side to Side Antenna Pattern

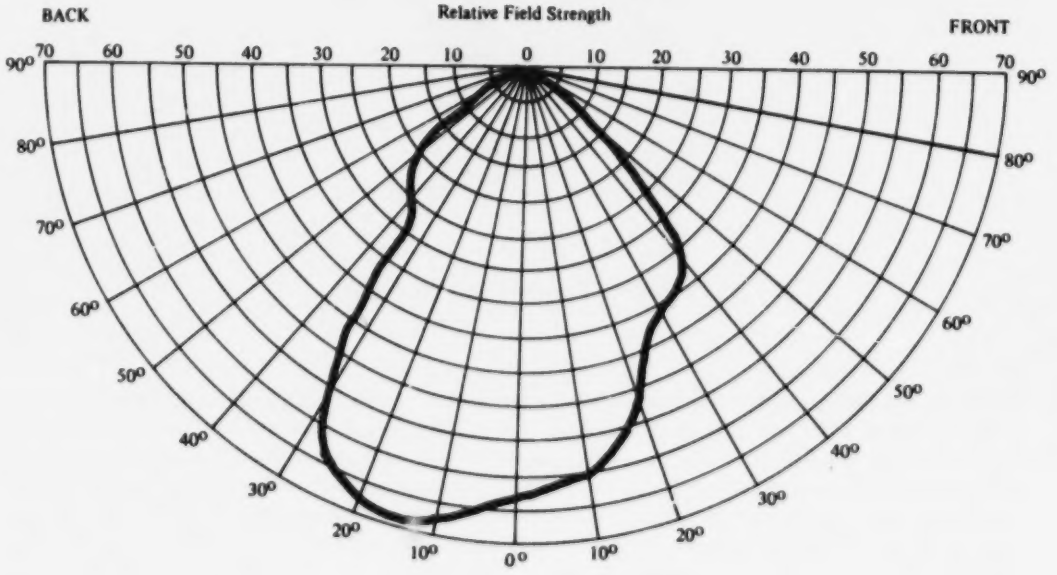


Figure 12. Front to Back Pattern

Note that the front-to-back pattern of the antenna is wide; therefore, as the antenna approaches targets, the targets come into the field of view when the line of sight between the target and the antenna is approximately 45°. The reflection from this target prints out at a depth that is equal to the "slant range" or distance between the target and the antenna. This distance is greater than the actual depth of the target. As the antenna approaches the target, the depth printout approaches the actual depth. This can be seen more clearly by studying the sample printout of a pipe target shown in Figure 13. The "tails" on the pipe signature are the reflections from the target when the antenna is at a 45° angle to the target.

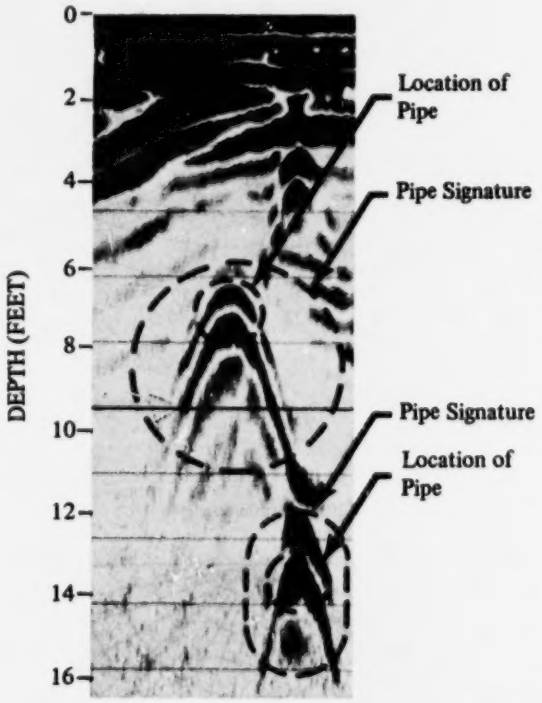


Figure 13. Example of Two Pipe Targets

On the other hand, the width of the beam or the width of the field of view in the side-to-side plane of the antenna is quite narrow, and objects or targets that are on the side of a particular survey path will not be recorded. Also, if light-reflection theory is assumed, plane surfaces such as interfaces will reflect energy from that portion of the beam that is normal to that surface. As the slope of this surface approaches 45°, and gets steeper than 45°, the ray of energy from the antenna at the normal angle to that surface is getting considerably weaker. Therefore, surfaces making an angle greater than 50° with the ground surface will not be detected by the system.

Once the impracticality of the test pit for geological studies was determined and the radiation characteristics of the antenna were measured, a program of field studies was undertaken. These studies were confined to areas subjected to continental glaciation in the recent geologic past. Several basic types of material are found in and around such areas. These materials are gravel, sand, silt, clay, glacial till, artificial fill, and bedrock.

Textural classification of mixtures of the above materials in this report will be made in accordance with the Triangular Classification Chart developed by one of the divisions of the U. S. Corps of Engineers (see Figure 14).

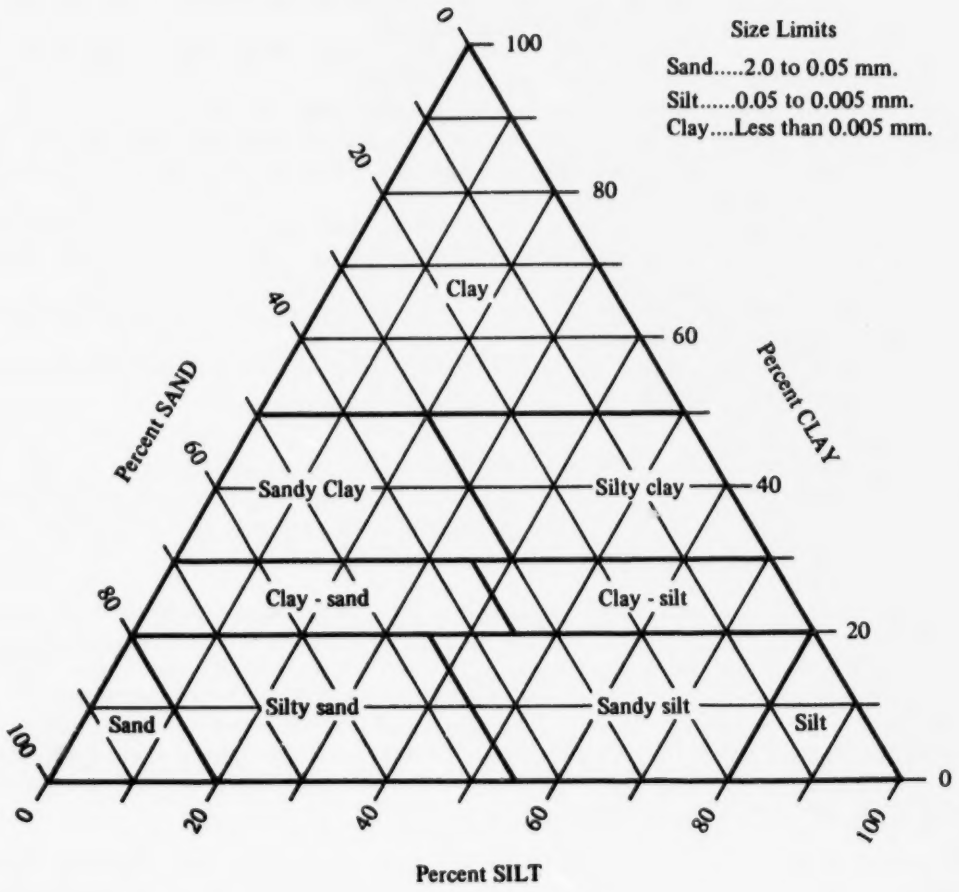


Figure 14. Textural Classification Chart

The nature of unlithified deposits and their relationship to bedrock in non-glaciated areas varies considerably. Most of the materials are found in both glaciated and non-glaciated areas; the ESP System's operation in materials from non-glaciated areas will not differ much from the materials tested except where different chemical properties result in gross differences in the electrical properties of the soils. For example, silty-sand in a non-glaciated region could be expected to have the same system charecteristics as the silty-sand in a glaciated area, but would be quite different if the sample had a high salt content. A highly generalized map of the major deposits of unlithified materials found in the contiguous U. S. is shown in Figure 15. Selected characteristics of most deposits are briefly discussed.

Wind-Blown Deposits - These include both silt and sand; high concentrations of salts exist in some areas of these deposits.
Saprolite - This generally consists of massive clay. The contact with unweathered bedrock is generally gradational.
Coastal Plain Deposits - These are generally sand, silt, or clay. The water table is high and swamps are numerous, particularly near the coast.
Desert Deposits - These are generally dry sand, silt, or clay. Caliche may be present in some areas.
Basin Deposits - These are generally dry silt and clay in low areas surrounded by sand and gravel. Deposits and groundwater may be highly mineralized. Caliche is common in some areas.
Alluvium - Materials present are variable. The water table is high in many areas; it may be highly mineralized.
Lake Deposits - These are generally silt and clay. Deposits and groundwater may be highly mineralized.

Field investigations of each of these non-bedrock materials, as well as bedrock, were conducted in natural situations. These field results are included in Appendix A. Laboratory investigations of these materials were also conducted and the results of the laboratory tests were compared to the field results.

Results of the investigations allow a prediction of the effectiveness of ESP methods in most glaciated areas. In areas where the overburden materials are sand or silty sand, depth of penetration is excellent, being as much as 25 to 30 feet in good conditions, and as much as 10-feet where lossy conditions exist. System resolution is 2- to 3-feet depending on the saturation of the material in the area. The number of interfaces penetrated is high; examples in the data show as many as 6 interfaces. The data received in areas of sand and gravel deposits clearly show the geological formation of the area. The patterns are distinctive and these areas are thus easy to classify.

Where the overburden is till, penetration depth is dependent on attenuation characteristics. Attenuation is high in till with high clay content, and depth of penetration is correspondingly low. The presence of clay in the overburden greatly decreases the capacities of the system, although some information can be collected. The operation of the system depends on the percent of clay in the material and the moisture content of the material.

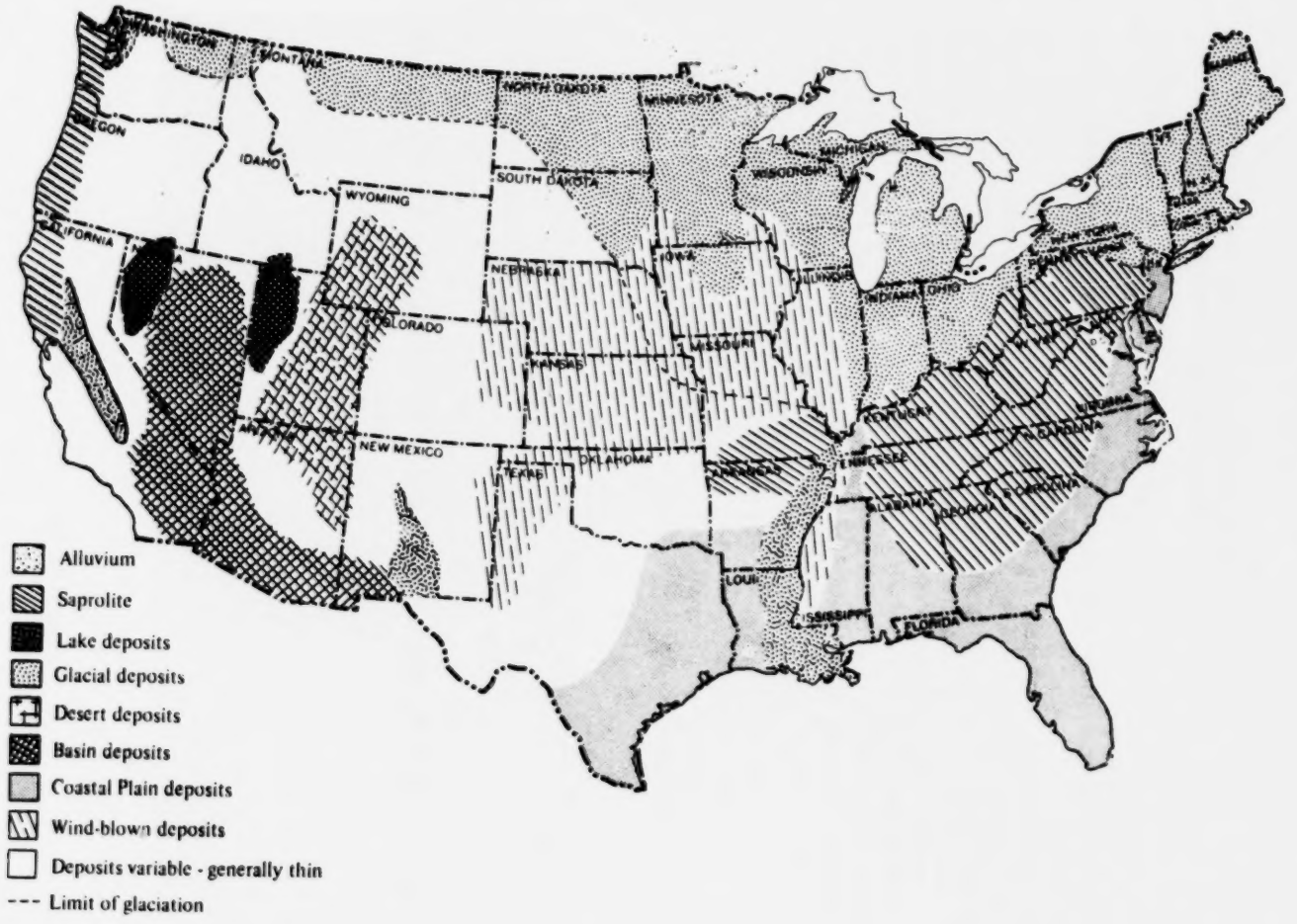


Figure 15. Map of Unlithified Materials

The location of bedrock with the ESP System is a complex and difficult task; however, success has been experienced using the following technique:

1. The ESP data are recorded.
2. An evaluation of the site is performed by an experienced geologist.
3. The ESP data are examined for one of the characteristic signatures of bedrock.
4. One or two of these areas are tested with a boring for material identification.
5. The interpretation is completed using the boring information as a guide.

Laboratory measurements were made on the soil samples collected in the field. To determine the ESP System's response to specific soil materials, one must know the electrical properties of these materials as they appear to the transmitted pulse. To measure these properties, a standard coaxial transmission line is used. This coaxial line, shown in Figure 16, is filled with the material sample to be measured and is packed to the desired density. The nature of the coaxial line lends itself nicely to pulse measurements and Time Domain Reflectometry (TDR) (Ref. 2). Figure 17 illustrates the effects on a pulse as it propagates along the transmission line. At each interface part of the pulse is reflected and part is transmitted. Figure 18 is a block diagram of the test set-ups used. Results of these measurements and the physical properties of each sample are presented in Table I. These results provide a record of the data collected on a particular sample and can be used in the calculation of various electrical properties of the samples. From these laboratory measurements, the velocity of propagation and the amount of attenuation are directly determined. The dielectric constant and conductivity are then calculated.

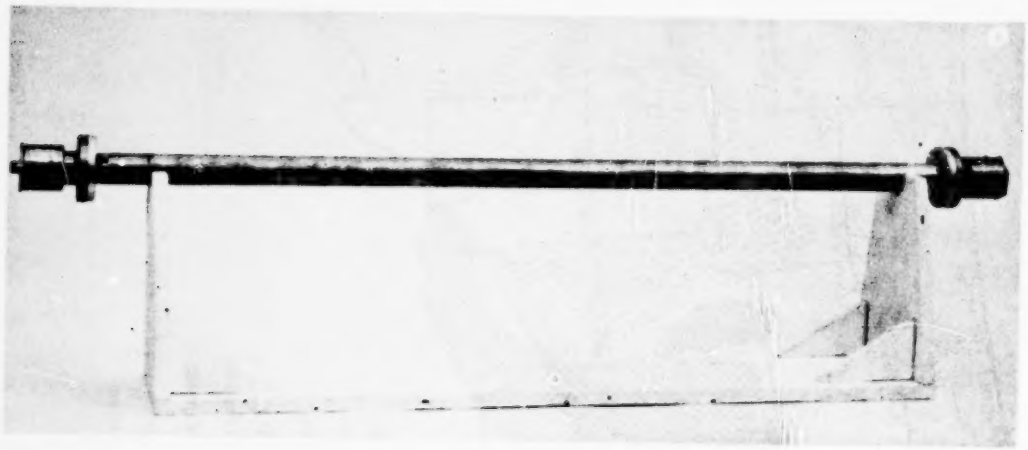


Figure 16. Coaxial Transmission Line

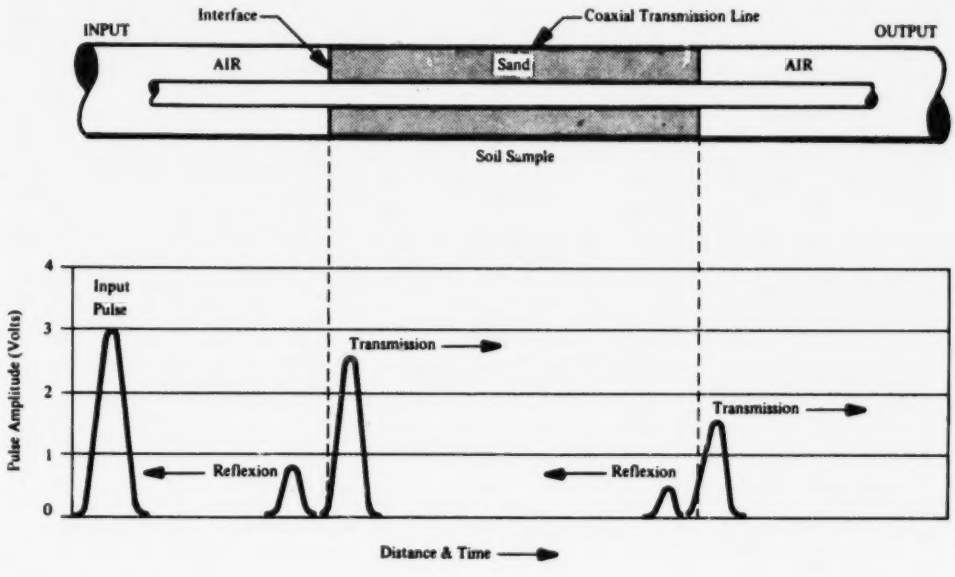


Figure 17. The Effects of Interfaces on a Video Pulse Travelling Down a Coaxial Line

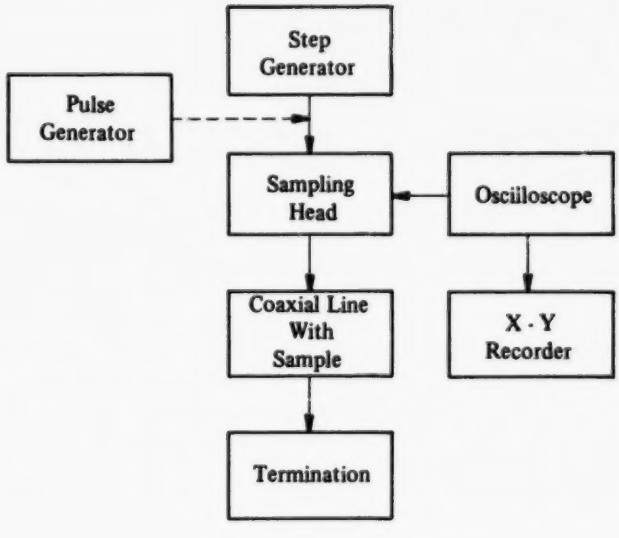


Figure 18. Block Diagram of Measurement Set-Up for Pulse And Time Domain Reflectometry Measurements

SAMPLE	CLASSIFICATION	UNIT WT DRY	MOISTURE CONTENT %	% SATURATION (WATER)	SAND %	SILT %	CLAY %	DIELECTRIC CONSTANT METHODS		ATTENUATION db
								PULSE	TDR	
0016 - 1	SAND	109.4	2.36	12.2	98	2		4.0	3.7	
0016 - 2	SAND	96.7	5.39	30.0	98	2		5.7	5.5	2.9
0016 - 15	SILTY SAND	99.5	55	2.19	46	36	18	7.0	6.2	8.5
0016 - 15a	SILTY SAND	72.4	7.65	29.12	46	36	18			15.0
0016 - 25	SAND	89.83	3.326	10.2	82	18		4.7	4.7	2.7
0016 - 25a	SAND	90.0			82	18		2.4		1.8
0016 - 27	SILTY SAND	91.29	1.97	6.1	74	26		3.1	3.1	2.9
0016 - 27a	SILTY SAND	90.6	4.85	15.6	74	26		4.6		7.3
0016 - 30	SILTY SAND	87.2	12.37	38.5	68	30	2	6.7	6.9	2.8
0016 - 36	SILTY CLAY	72.67	25.22	92.3	1	56	43		10.0	9.6
0016 - 37	SAND	97.6	2.466	9.5	100			4.8	4.8	2.0
0016 - 37a	SAND	96.7	5.99	22.4	100			6.8	6.3	3.2
0016 - 37b	SAND	105.0			100			2.6		
0016 - 38	SAND	94.14	4.1	14.3	100			4.5	4.5	1.8

Table 1. Properties of Selected Soil Samples

The ESP System detects dielectric interfaces, that is, the interface between two materials, by detecting the change in dielectric constants as it passes through these materials.

As a first approximation, the dielectric constant of the sample material is calculated from the two-way transit time through the material in the transmission line. This can be measured two ways. It can be measured by using the pulse method shown in Figure 18. This measurement results in a curve as shown in Figure 19. Three distinct pulses can be seen on this trace. The first and largest pulse is the incidence or transmitted pulse. The second pulse is the first reflection or the reflection of the pulse from the beginning of the material packed in the sample tube. The third pulse is the reflection of the pulse at the end of the sample tube. The time between the first and second reflection pulse is the two-way transit time through the material and is measured between the peaks of the pulse. This time is accurate to within plus or minus one nanosecond. The dielectric constants presented in Table 1 are calculated using this time and the sample length in the following equation:

$$=\left(\frac{ct}{2L}\right)^2 \qquad (7)$$

where:

c = velocity of light, 3 x 10^8 meters/sec
t = time between pulse peaks
L = sample length in meters

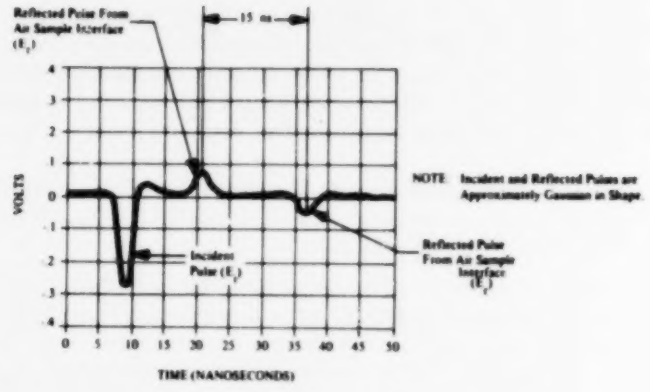


Figure 19. Example of Data Using Pulse Method

The second method to determine the two-way transit time uses time domain reflectometry. The equipment set-up for this method is also shown in Figure 18. This is a standard technique for determining the impedance of a transmission line (Ref. 2). The transmission line (see Figure 16) used to hold the sample is a 50 ohm impedance air dielectric line. The resulting waveform from a test of this line without a sample in it, that is, simply as an air line, would be a straight line trace indicating that there are no impedance discontinuities along the line. However, when the line is packed with a soil sample, the dielectric constant of the soil sample is different from that of the air and causes a change in the impedance of the transmission line. In the example shown in Figure 20, the soil-filled coaxial line has a lower impedance than the air-filled line. The second discontinuity occurs at the point where the sample ends and the line is again 50 ohms. The distance between these discontinuities is the transit time in the sample material.

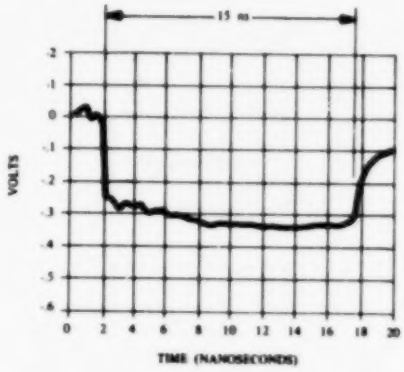


Figure 20. Example of Data From TDR Measurement

The velocity of propagation of the pulse through the samples is calculated from this transit time. Knowing the length of the transmission line and the transit time one can compute the velocity of propagation directly, since velocity equals length (or distance) divided by time. This velocity of propagation for each geological material is used to calculate a scale factor for determining the depth scale on the ESP profiles.

Both pulse and TDR measurements were made on all the samples tested, and the dielectric constant and velocity of propagation were calculated from both methods, thus providing a cross-check on the measurements.

Attenuation is a measure of the amount of energy that is dissipated or lost as the pulse passes through a material. Figure 21 is a block diagram of the test set-up to measure the pulse distortion and attenuation through the sample, using an insertion technique. The pulse shape before it enters the material is found by connecting the pulse generator directly to the sampling head of the oscilloscope and recording this pulse on the XY recorder. The sample-filled coaxial line is then placed between the generator and the sampling head and the pulse shape is recorded, thus giving the shape of the pulse after it has passed through the material. A sample of this data is shown in Figure 22. The difference between the peak level of the two pulses is a measure of the energy lost in passing through the material. The results of the attenuation measurements are listed in Table 1

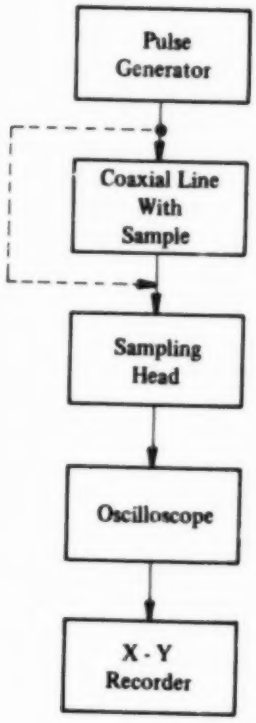
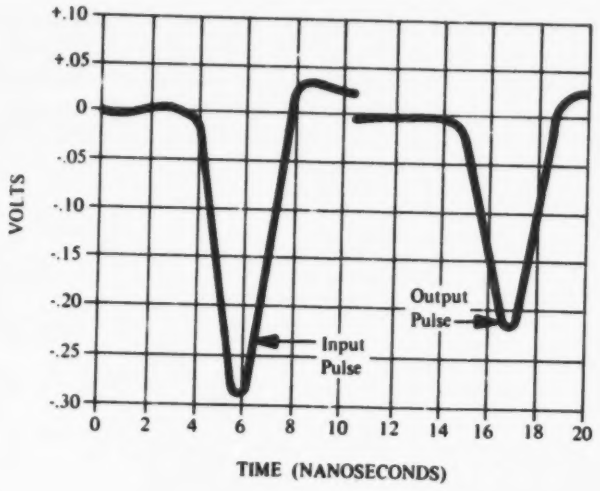


Figure 21. Block Diagram for Attenuation Measurement



NOTE: Input and Output Pulses are Approximately Gaussian in Shape.

Figure 22. Example of Data From Attenuation Measurement

By comparing the results of the attenuation measurements for the different materials with the ESP data collected in the field, it is possible to estimate the depth of penetration in each particular material.

All collected soil samples were subjected to a grain size analysis using standard seive analysis techniques. Where necessary, hydrometer measurements were made to determine the content of silt and clay. Moisture content was measured on all samples, and where possible, in-place density measurements were made. From these data the percent saturation was calculated. This information was collected in order to have a classification cross reference to the electrical measurements made on these samples.

Table 1 includes a summary of the physical characteristics of the samples measured in the laboratory. Soil moisture has a great effect on dielectrical constant and the other related electrical characteristics. All initial measurements were made on the soil samples as they were received from the field.

To gain further insight into the effect of moisture on these electrical characteristics, the moisture content of selected samples was adjusted and additional electrical measurements were made. The moisture content of three sand samples was increased to approximately 5% by adding water; two samples were dried. In an attempt to determine the relationship between moisture and dielectric constant, the values for these two characteristics were plotted against each other. The results were scattered and no conclusions could be drawn. This is understandable since electrically the soils are a composite material made up of the soil grains, air and water. In a given sample the variables are the air and water. The dielectric constant of a particular sample is determined by the percentages of the three components on a volumetric basis and so varies with each sample. The moisture content measurements, on the other hand, are based on the dry samplw weight and so do not provide a good basis for direct comparison of results.

To overcome this disparity, the percent saturation was calculated for each of the samples. This is a measure of the percentage of the air voids that are filled with water, and is therefore a measure of the water content of the sample on the volumetric basis. The calculated dielectric constant of the samples were then plotted against percent saturation and the results are shown in Figure 23. Note that the data follow a predictable trend.

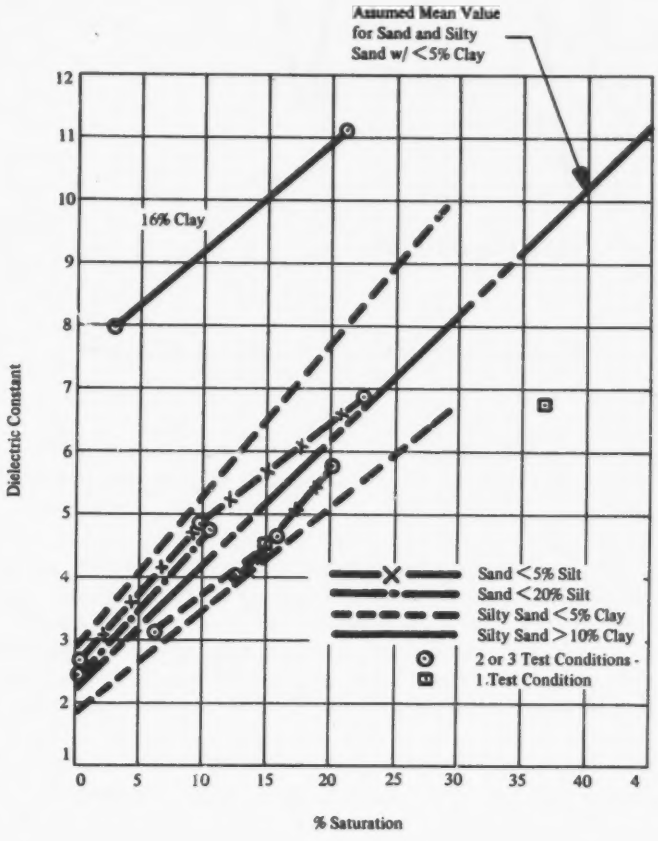


Figure 23. Dielectric Constant vs. % Saturation

The indications from the test data are that the dielectric constants for dry sand samples with up to 30% silt are all within the range of 1.5 and 3.0. As the water content of the material increases the dielectric constant increases, with all the materials showing the same effect. A zone is marked off on the dielectric constant-saturation curve that includes a spread of plus or minus 10% in scale factor. The mean value of the dielectric constants is also plotted. Based on available data, if the dielectric constant indicated by the mean curve for a given percent saturation were used to determine the scale factor on the ESP profiles, the maximum error would not exceed $\pm 10\%$.

Samples taken from the borings (which will normally be done on all jobs) can be analyzed for sand, silt and clay content, and for percent saturation. A reasonable scale for the area then can be selected. More testing is required in cases where the clay content of the soil is up to 20% , but the indications are that the same regularity of results will exist and that a method for scaling can be developed for these materials as well.

Examination of the attenuation values shown in **Table 1** indicates that this characteristic is not as easy to classify as the dielectric constant data. However, the attenuation levels for sand and silty sand are 1.5 to 4.0 db, while the attenuation level for materials with high clay content is between 8.0 to 15.0 db. It can be seen that this characteristic is borne out in the field investigations where depth of penetration in clay materials is limited to depths of approximately 5 feet.

Figure 24 shows the 0 to 10-foot scale to be used on the profiles of the ESP System for the different materials evaluated. There is a large variation in the scale between samples of dry sands and samples with high clay content. This is not a problem since large areas to be investigated with this system would consist of materials of like characteristics, and when materials with much different scale factors are present they would also exhibit very large dielectric constant contrast. As is discussed in the evaluation of the dielectric constant data, a method is available for determining the correct scale factor in the field. As a calibration test, scans were taken over pipes at known depths in one of the test sites. In order to have the pipe installed at the known depth but still have an undisturbed overburden, a site was selected with a cut bank running parallel to the scan path. The pipe was buried under the scan path through the cut bank at a given depth. Scans were taken with the pipe at three different depths. The printouts of these tests are shown in Figures 25, 26 and 27. The actual depth of the pipe is shown in the figure, as well as the depth that would have been determined by the relevant scale factor.

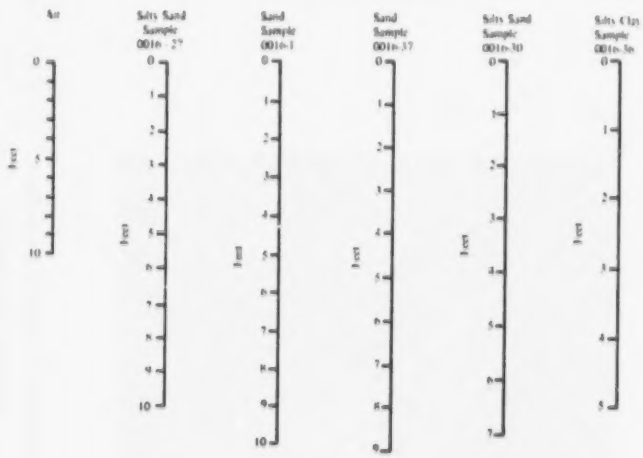


Figure 24. Comparison of Depth Scales for Various Samples

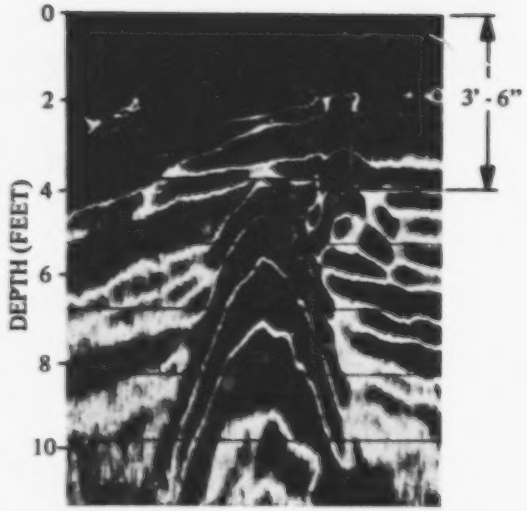


Figure 25. 1" Diameter Calibration
Pipe 3'-6" Deep in Sand

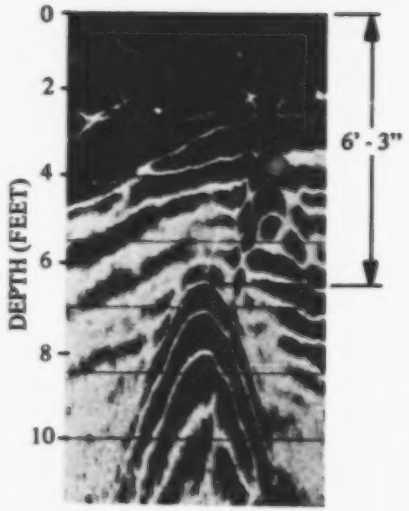


Figure 26. 1" Diameter Calibration
Pipe 6'-3" Deep in Sand

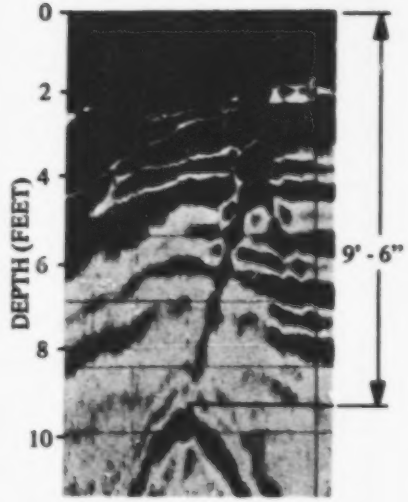


Figure 27. 1" Diameter Calibration
Pipe 9' - 6" Deep in Sand

SECTION VII

UNDERGROUND PIPES AND UTILITIES

The ESP System can be used to locate underground pipes and utilities. Laboratory tests were performed to gain an understanding of the **ESP System**'s capabilities for detecting various types of pipe.

A series of laboratory tests determined the system's response to different pipe materials. A trench approximately 120 feet long was dug and selected pipe samples were buried at various depths (see Figure 28). The material in which the pipes were buried is a clayey till, similar to Sample 0016-15 (see Table 1). As was discussed in the section on geological investigations, this and other materials with high clay content decreases the system's penetration ability. This makes clayey material a good medium to test performance on pipes since it will be possible to bury pipes at or below the penetration limits. ESP measurements were taken across the top of each pipe and the data were recorded. Figures 29 through 39 are the data printouts of these measurements.

The following conclusions were drawn:

1. Pipes at depths less than 2-feet are easily detected with this system. The reflected signal is superimposed on the surface reflection oscillations; however, the pipe reflection is easy to pick out.
2. The maximum depth at which metal pipes can be detected in this material is probably not more than 5-feet. Maximum detection depths in other materials will be the same as in the geological tests, that is, 10-feet for tills with negligible clay content, and up to 25-feet in sand.
3. The non-metalic pipes do not return a strong reflection and in some cases are impossible to detect. Concrete pipe cannot be considered a non-metalic pipe in this study since the pipe contains metal reinforcing wires. The results of the plastic pipe measurements prompted further studies on plastic pipe.

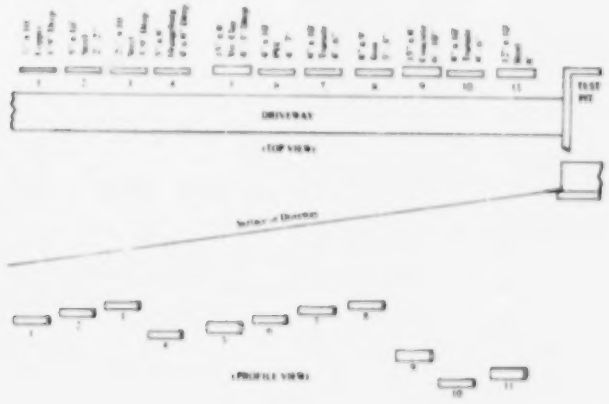
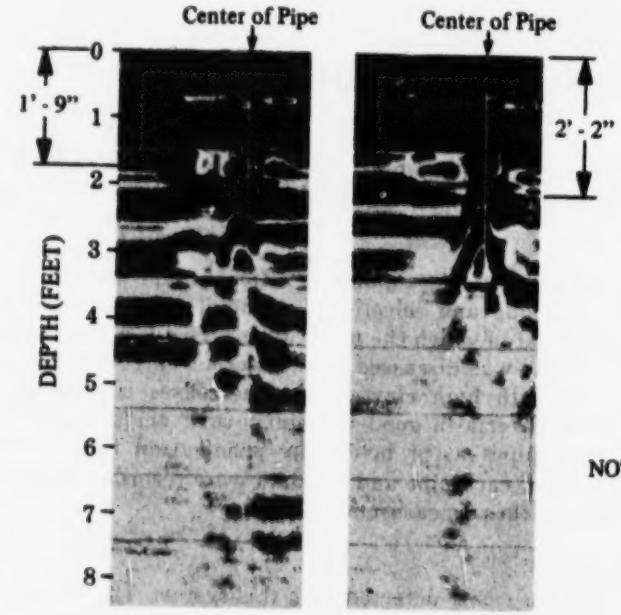


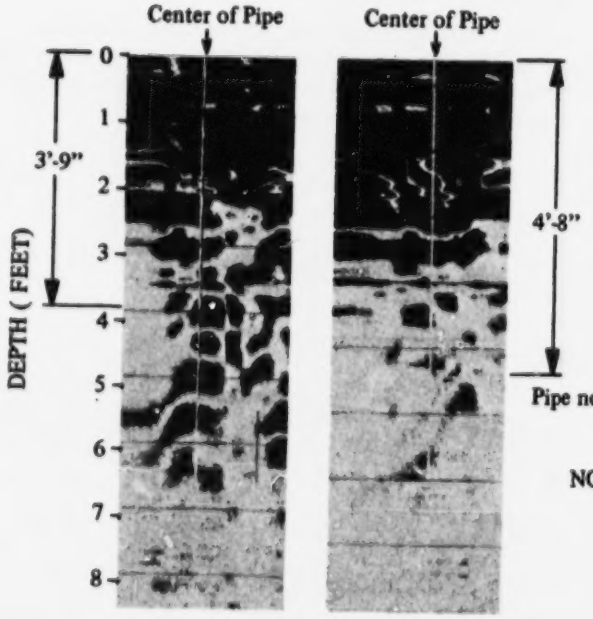
Figure 28. Location and Depth of Various Pipe Samples



NOTE: Dimension of side of figure is measured depth to top of pipe.

Figure 29. ½" Diameter Copper Pipe

Figure 30. 5" Diameter Steel Pipe

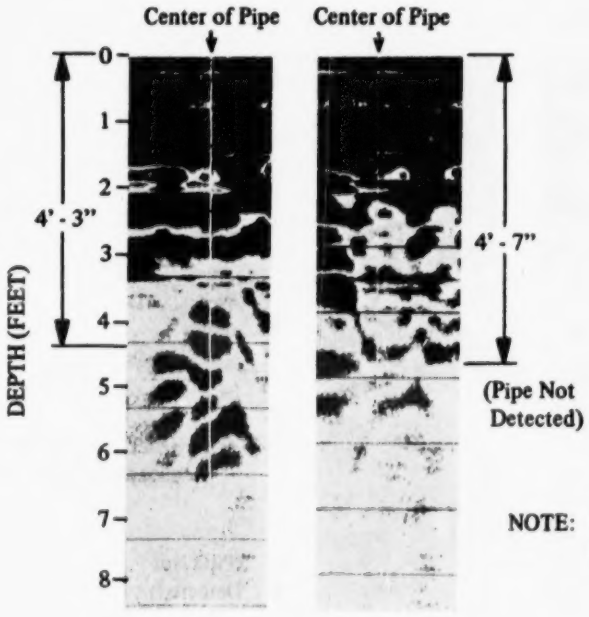


Pipe not detected

NOTE: Dimension of side of figure is measured depth to top of pipe.

Figure 31. 2½" Diameter Steel Pipe

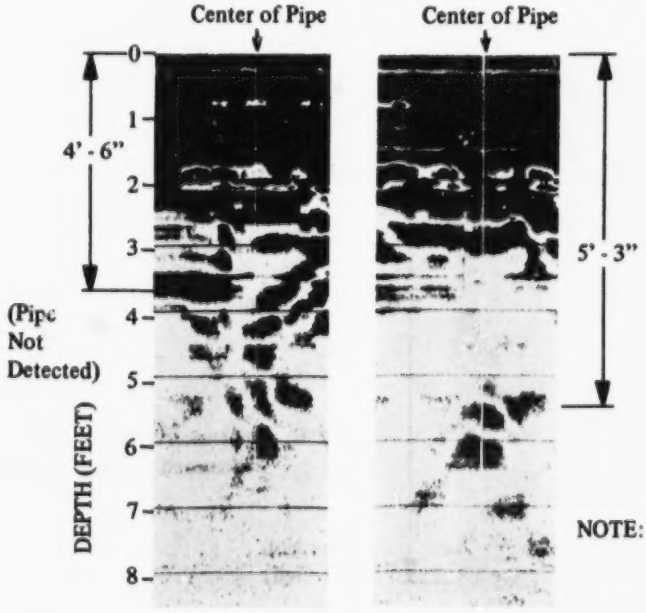
Figure 32. 5" Diameter Orangeburg Pipe



NOTE: Dimension of side of figure is measured depth to top of pipe.

Figure 33. 15" Diameter Vetrified Clay Pipe

Figure 34. 4" Diameter PVC Pipe



NOTE: Dimension of side of figure is measured depth to top of pipe.

Figure 35. 7" Diameter Transite Pipe

Figure 36. 8" Diameter Steel pipe

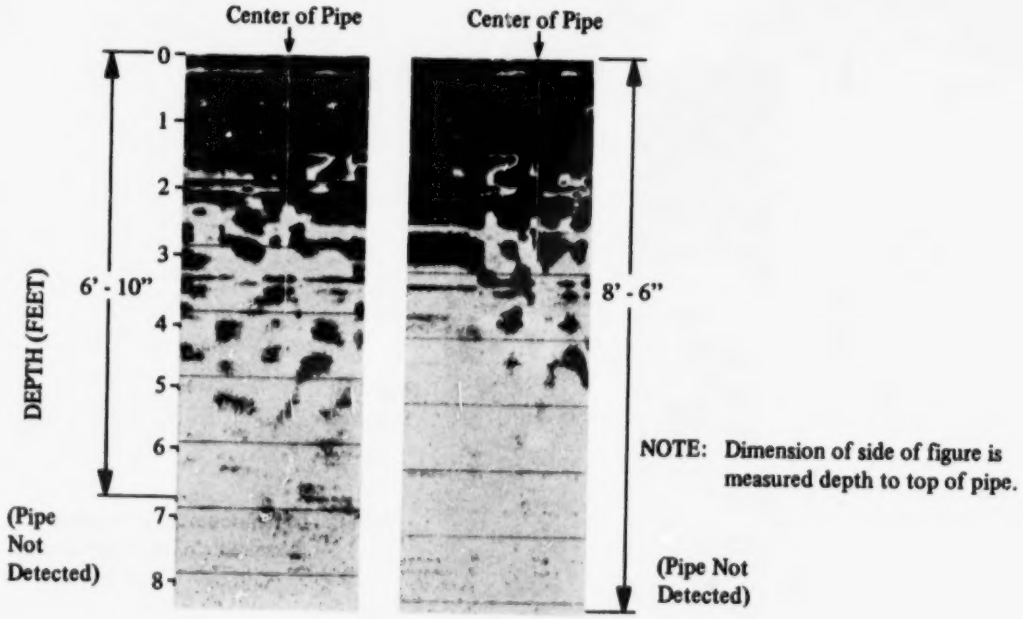


Figure 37. 15" Diameter Concrete Pipe

Figure 38. 7" Diameter Transite Pipe

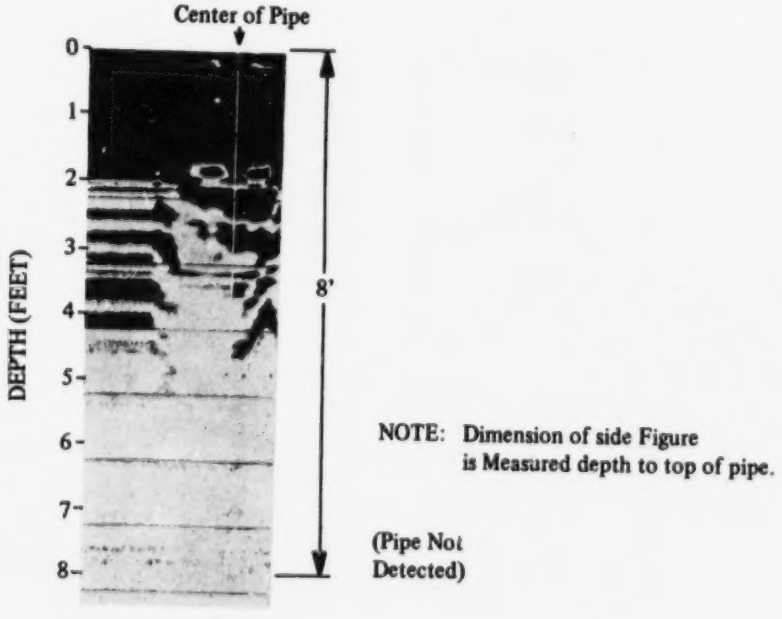


Figure 39. 12" Diameter Steel Pipe

Two pipes were installed in the test pit (see Figure 40). One of these, a 12-inch diameter steel pipe, was installed as a target in the study of the antenna system, and as a model from which the normal signature of a pipe could be determined. To further investigate the problems of detecting non-metallic pipe, a specially designed PVC pipe was installed in the test pit. This pipe was fitted with end caps and hose fittings, which allowed the pipe to be filled with water or drained as desired. It was reasoned that the poor results on non-metallic pipe in the test trench was caused by an insufficient difference between the dielectric constant of the pipe material and the surrounding soil. In actual conditions these pipes may contain water or a fluid with a very high percentage of water. If the ESP System cannot detect the pipe, then it should detect the contained fluid. ESP measurements were made across the top of this pipe under both the filled and empty conditions. Figure 41a is the reflection of the empty pipe and Figure 41b is the reflection of the pipe filled with water. The PVC pipe filled with fluid was easily detected by the ESP System. Another experiment included attaching a thin wire along the length of an empty PVC pipe. The ESP measurements showed that the pipe with the wire was detected, while the PVC pipe without the wire was not detected.

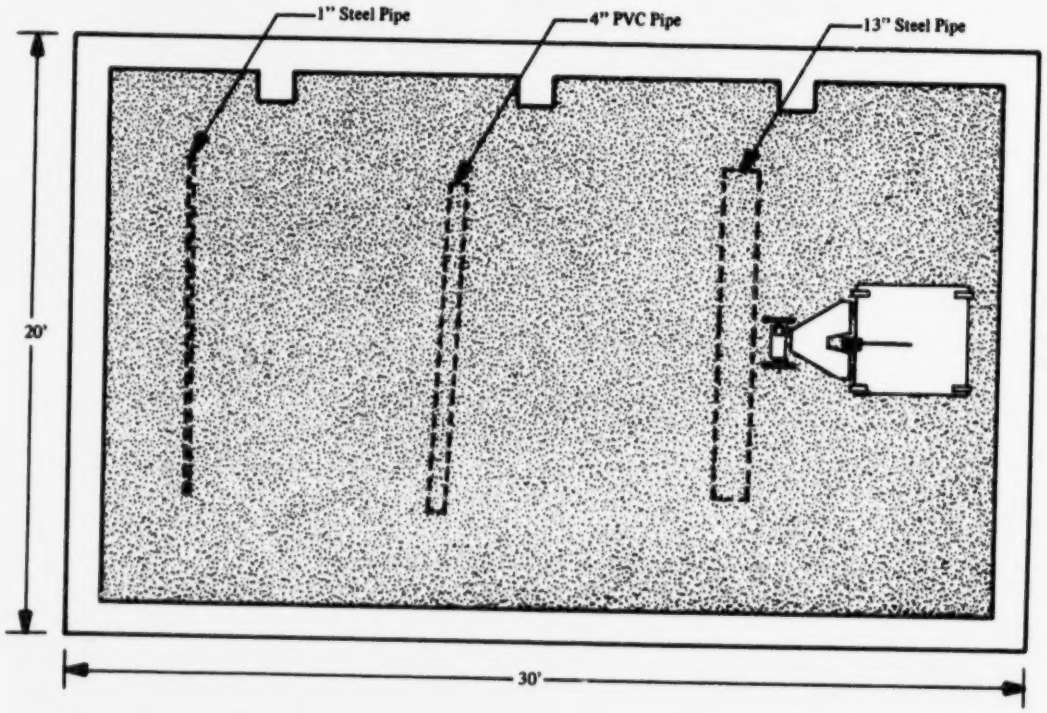
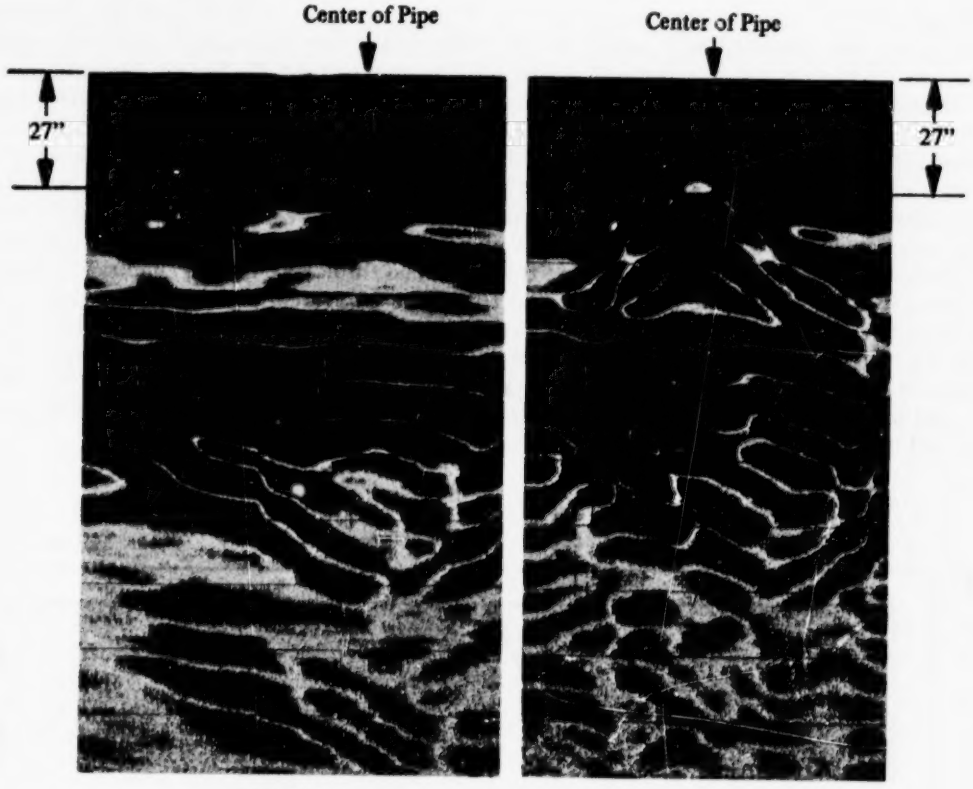


Figure 40. Test Pit with Pipes



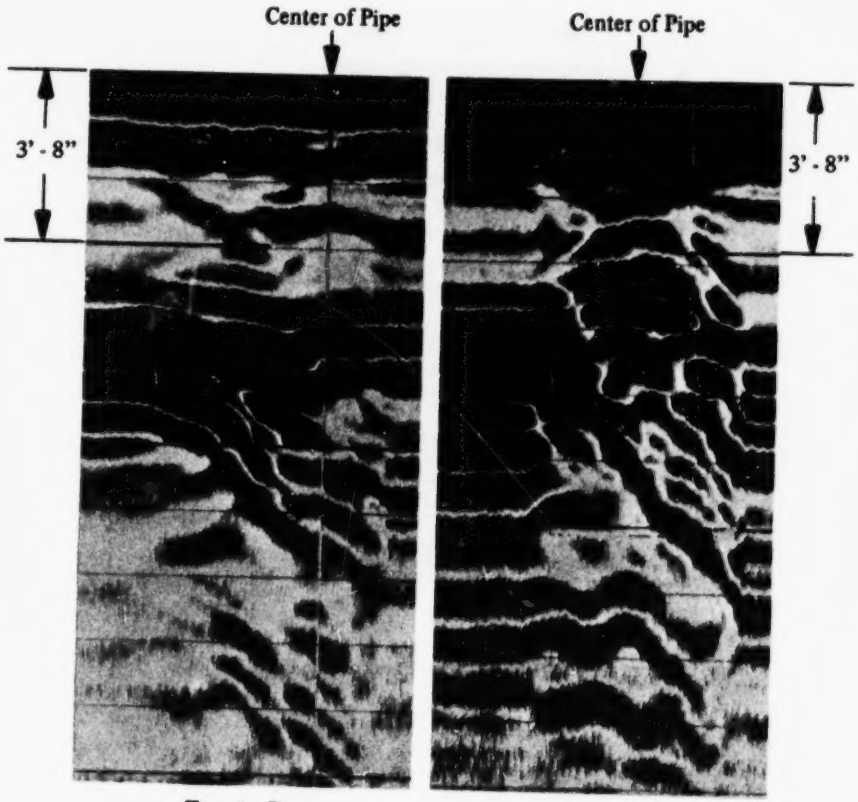
a. PVC Pipe
Empty

b. Water Filled
PVC Pipe

NOTE: Dimension of side of Figure is
Measured Depth to top of Pipe.

Figure 41. 4" PVC Pipe 27" Deep

An experiment was conducted to determine the capability of the system to detect a damaged pipe. The pipe used in the experiment was an 8-inch transite pipe fitted with hose connections to allow filling and draining it with water. Because transite pipe is non-metallic it is difficult to detect when empty. Its dielectric constant is close to that of the surrounding materials and so does not give rise to a strong reflection. This is shown in Figure 42a which is a crosscut over the dry transite pipe. The known location of the pipe is indicated on the figure; there is a weak reflection. This would make the detection of a damaged, unused transite pipe very difficult; however, the situation for this pipe filled with water or with an organic material is quite different. In Figure 42b, which is a crosscut over the same path as in Figure 42a, the water-filled pipe reflects a strong signal.



a. Transite Pipe Empty

b. Water Filled Transite Pipe

NOTE: Dimension of side of figure is measured depth to top of pipe.

Figure 42. 8" Transite Pipe 3' - 8" Deep

In the course of this experiment one of the end caps in the pipe had developed a slow leak. Figure 43 is a scan along the length of the water-filled pipe. The data show a strong reflection below the right-hand end of the pipe indicating a zone of saturated soil.

To obtain a damaged pipe situation, the pipe was drained and a small hole was augered from the ground surface to the top of the pipe. The auger was used to obtain a minimum disturbance of the material over the pipe. The pipe was then broken using a steel bar and a sledge hammer. The augered hole was backfilled and water was run into the pipe through the fill hose. Figures 44 and 45 compare the parallel and cross scans of the pipe before and after it was damaged. Note the differences in each scan caused by the saturated area below the pipe.

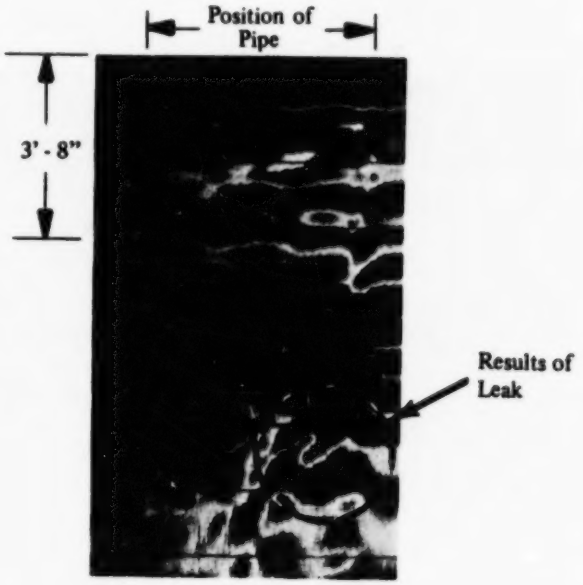


Figure 43. 8" Transite Pipe with Leak at One End

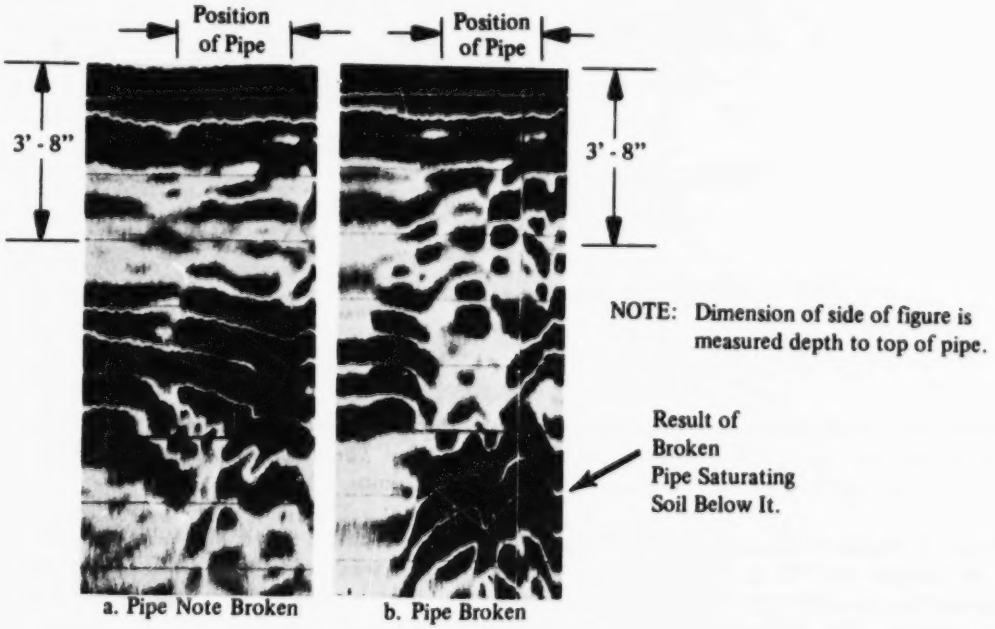
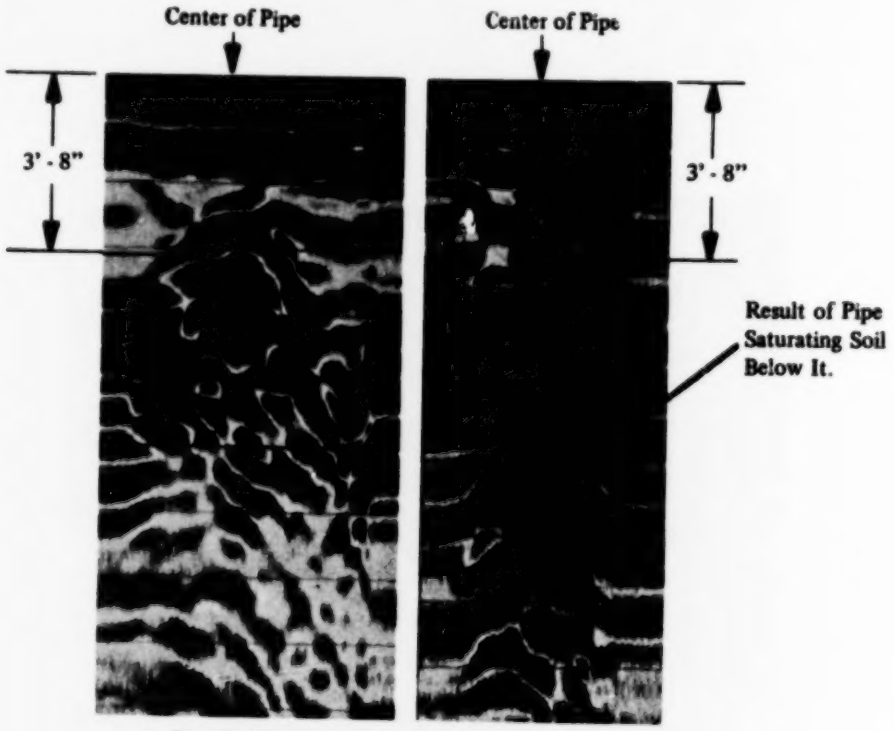

Position of Pipe
Position of Pipe
3' - 8"
3' - 8"
NOTE: Dimension of side of figure is measured depth to top of pipe.
Result of Broken Pipe Saturating Soil Below It.
a. Pipe Note Broken
b. Pipe Broken

Figure 44. Parallel Scan Along Transite Pipe Before and After Being Damaged



NOTE: Dimension of side of figure is measured depth to top of pipe.

Figure 45. Cross Scan Over Transite Pipe Before and After Being Damaged.

This experiment indicates that the system can detect damaged pipe by detecting the saturated zones in the vicinity of the break.

Field investigations were conducted to determine the capabilities of the ESP System to locate underground utilities in city streets. Samples of data collected in some of these investigations are included in this report and are shown in Figures 46 through 48. Figure 47 is an example of data collected in an area with a high utility congestion. The three scans were taken at 10' intervals across a city street. This is an example of the ESP System's ability to discriminate closely spaced pipes. Figure 48 is an example of data taken where trolley car tracks have been paved over and forgotten.

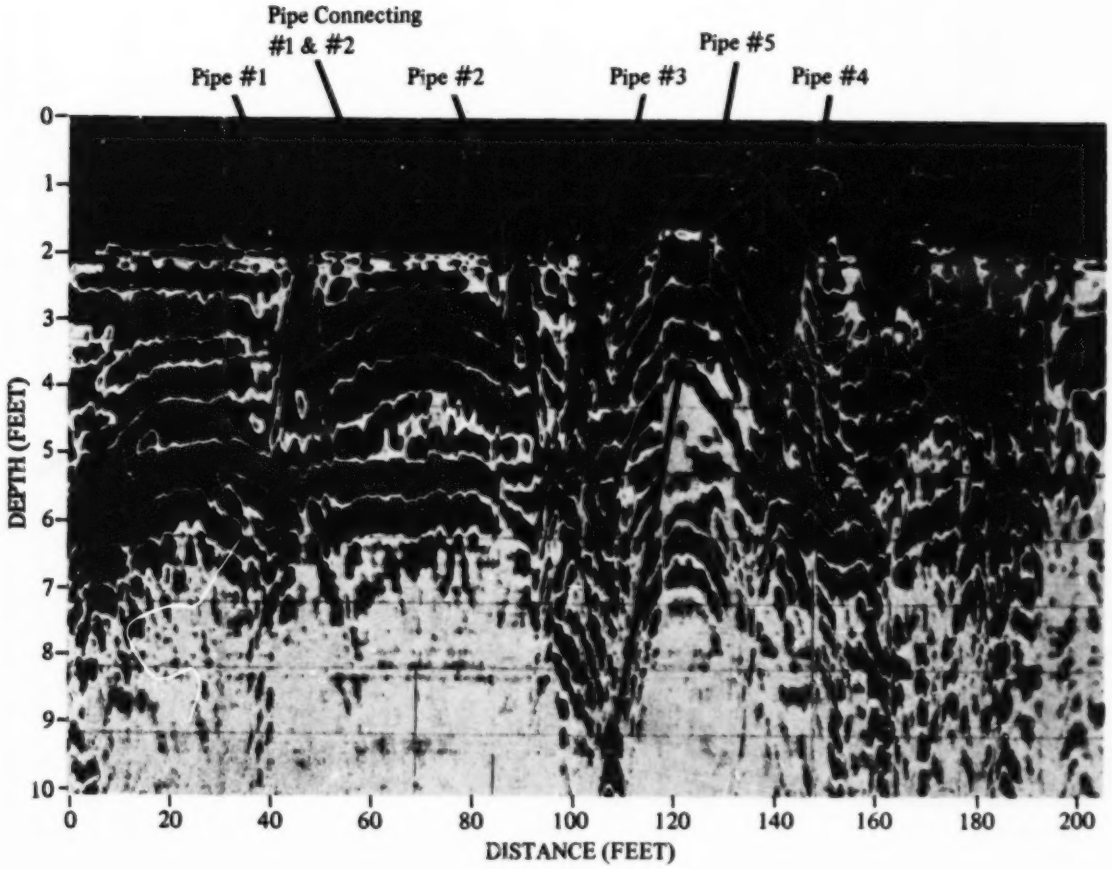


Figure 46. Example of Buried Utilities in Stratified Sand and Gravel

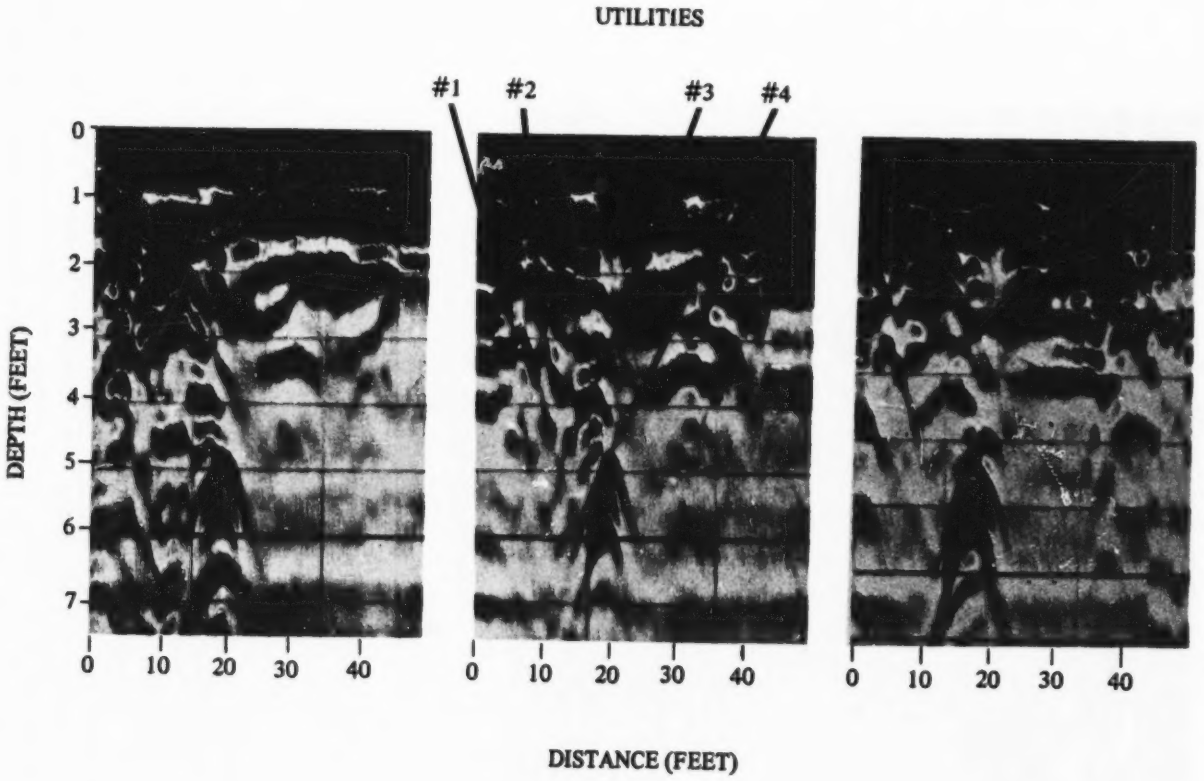


Figure 47. Three Scans Taken at 10' Intervals Across a City Street

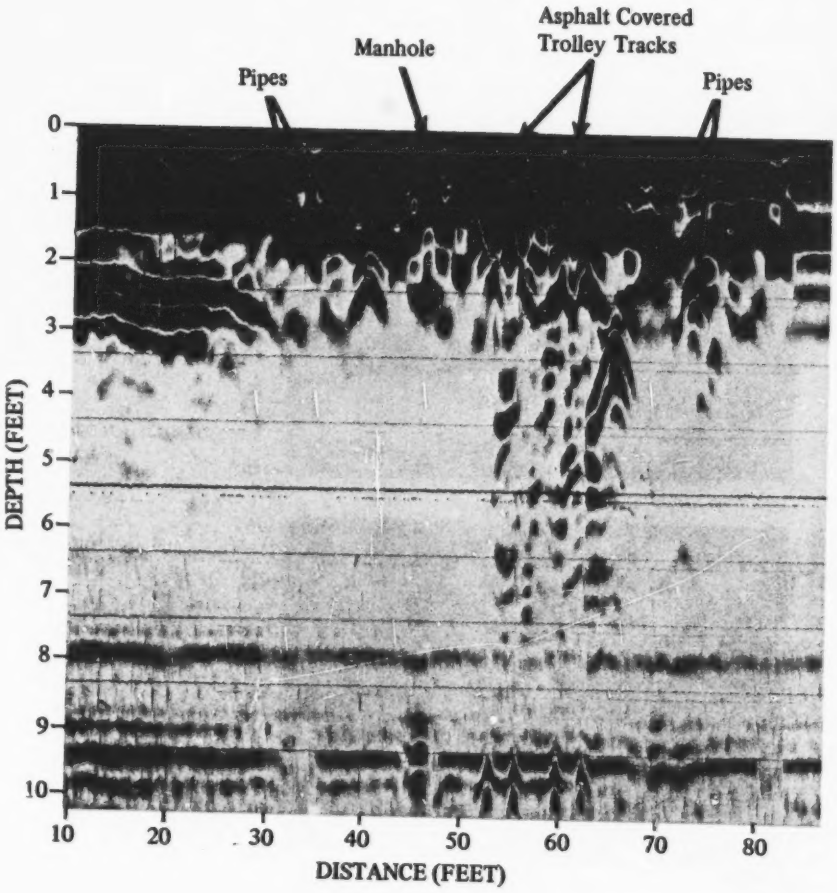


Figure 48. Intersection in Business District of a City (Lawrence, Mass.)

Many practical applications exist for the ESP System in locating utilities and other man-installed underground systems. It can be used when a system such as a sewage collection system is to be installed in the street and it is important to know the location and depth of water and gas services and storm drains that cross the trench path. In this situation a scan can be taken along the trench path; the pipes crossing the trench path can be located from the data. They can be shown either in a drawing or can be painted on the road surface. A second application exists where a sewer line is to be installed through an intersection containing a high congestion of utilities and manholes. For this investigation of utility location it is best to mark off a grid in the intersection and take data scans along the lines in the grid. The data are then evaluated in the laboratory and a map of the actual linear system locations can be constructed. Figure 49 is an example of the results of this type of utility location investigation.

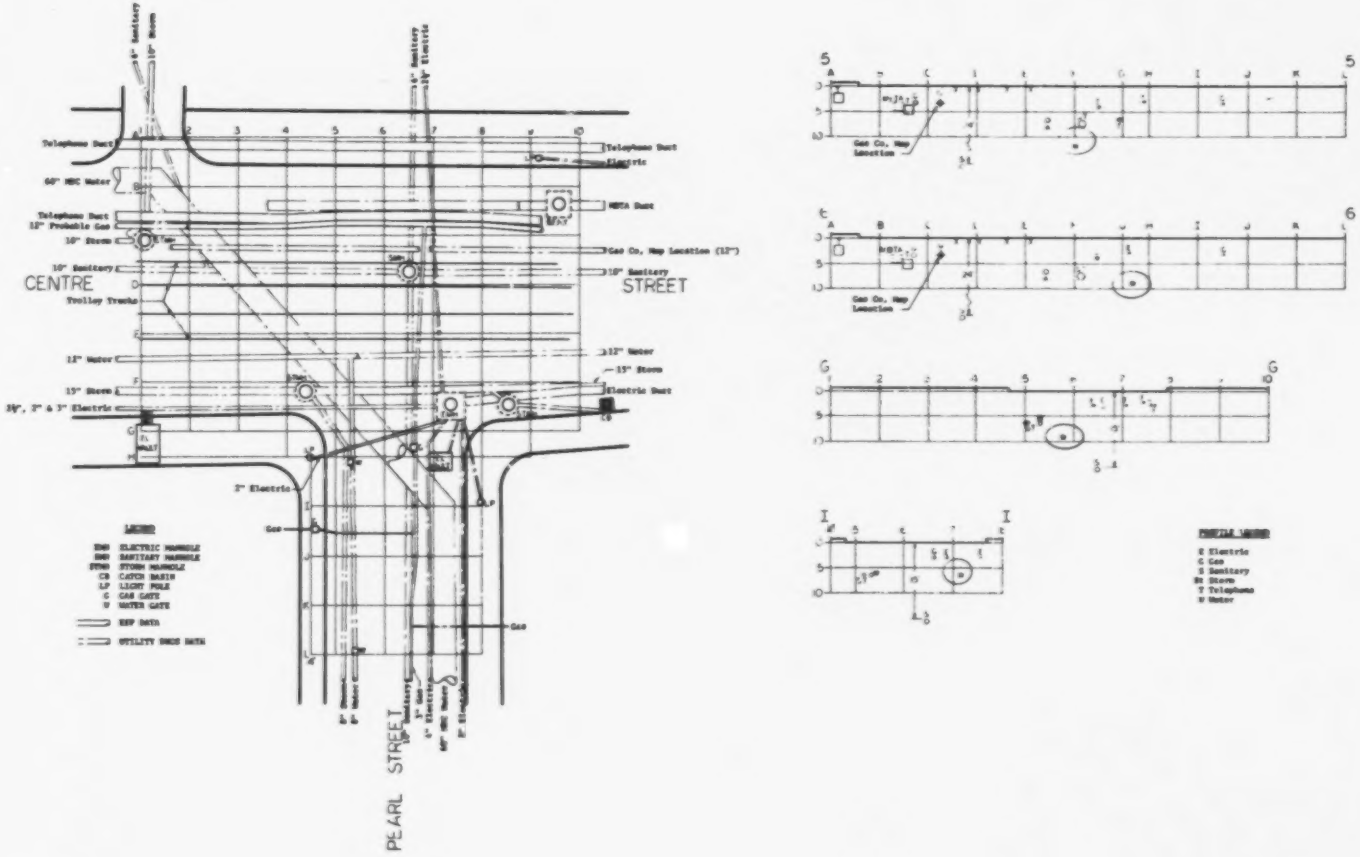


Figure 49. Example of Utility Mapping

SECTION VIII

APPENDIX

This appendix describes the field investigations of geological materials as they occur naturally. Laboratory investigations of these materials were also conducted and the results of the two investigations are compared.

A number of potential study areas were evaluated by the following criteria:

1. The area should have a minimum combination of materials and the material to be studied should be the major component.
2. Some method of physical examination should be possible along the path surveyed with the ESP System. The methods employed, listed in order of preference, are:
    a. excavation and visual examination;
    b. boring with a split spoon sampler; and
    c. examination of a cut zone parallel to the ESP survey path.

Sand

A site was selected in Groveland, Massachusetts, where sand could be studied by both the ESP System and by trenching. The area is a delta, common in glacial areas. The portion of the delta studied consisted of fine sand interbedded with minor amounts of both coarser and finer materials. Selected areas of the survey paths were trenched, examined, and mapped. Figures 50, 51, and 52 are data printouts from different areas in this site. The survey line shown in Figure 50 was selected for trenching because of the interesting feature in the geological deposits shown at Stake 2. A trench, varying in depth from 5-feet to 8-feet was dug by backhoe along this line, and the distribution of the various materials was mapped (see Figure 53). Samples of different materials were collected for laboratory analysis. The major portion of the sand-bedding in this survey line is much like sample 0016-25, which was taken from another area on the same site. The electrical characteristics shown in Table 1 for sample 0016-25 apply to this area.

In studying the geological mapping of these material deposits, there are some interesting features that can be used to evaluate the system's discrimination capability. There are both thick and thin deposits of material as well as a number of lensing situations (the thinning out of a stratum in one or more directions). The reflection oscillations in this material are 2 1/2-feet thick, meaning that the resolution of the system in this area is from 2 1/2 to 3-feet. Most of the strata in Figure 50 are less than 2-feet thick. This, and the fact that lensing exists, means that the picture printed out is a composite of the superimposed reflections of the various interfaces. Although distinct individual interfaces of the materials cannot be picked out of the data, the general characteristics show up well.

Figure 51 shows a printout of another survey line from the same site. The depth of penetration to the left of the printout is 2-feet, while 100-feet away at the right of the printout the depth of penetration is greater than 20-feet. This line was also trenched and a map of the materials is shown in Figure 54. Note the location of a stratum of material with a high moisture content. The effect of moisture content can be seen by referring to Table 1 and by noting the results of tests conducted on samples 0016-25, 27, and 37. These samples were tested at various moisture contents or percent saturation. The tests indicate that at-

Preceding page blank

tenuation increases with the percentage of water in the sample. The 8.2% moisture is equivalent to approximately 25% saturation. In Figure 51 the effects of attenuation became obvious. Above the critical layer the interfaces reflect strong, sharp bands, while below the critical layer the bands are weaker and indistinct. Also note that as the scan progresses from stake 3 to stake 9 reflections are received from more interfaces. At stake 4 there are reflections from approximately 4 interfaces. The reduction in the signal strength caused by increasing number of interfaces can be seen by tracing the lower interface in the printout from left to right.

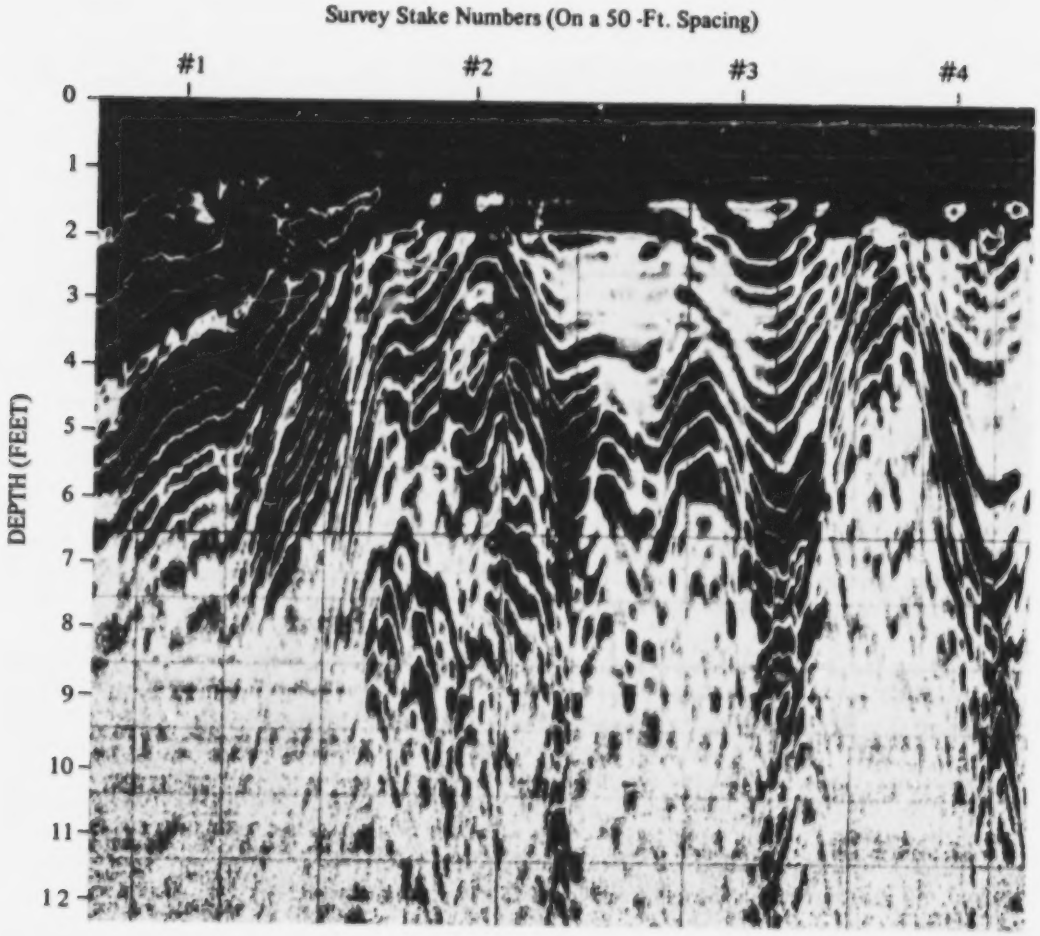


Figure 50. Delta From Groveland Test Site

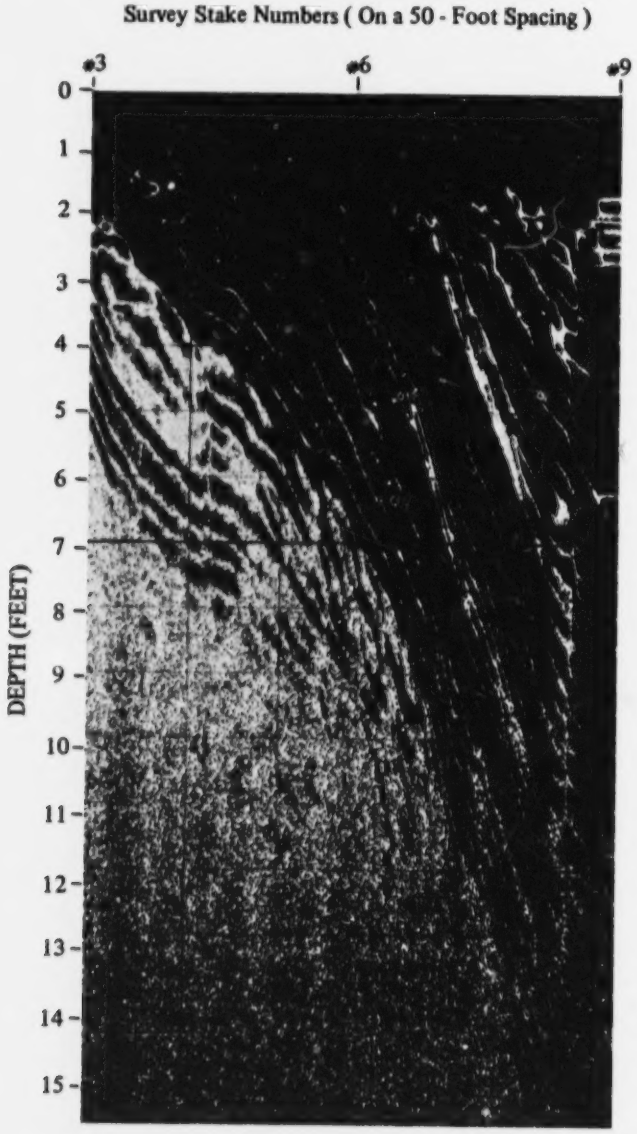


Figure 51. Data From Groveland Test Site

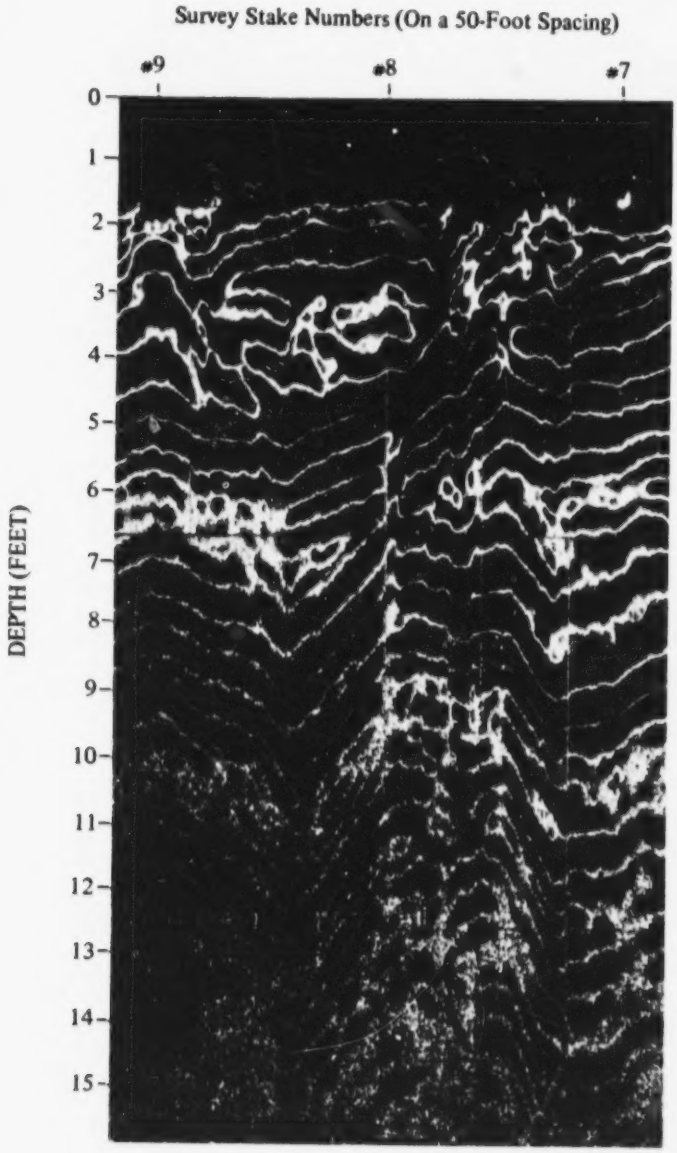


Figure 52. Date From Groveland Test Site (Scan is Perpendicular to scan in Figure 51)

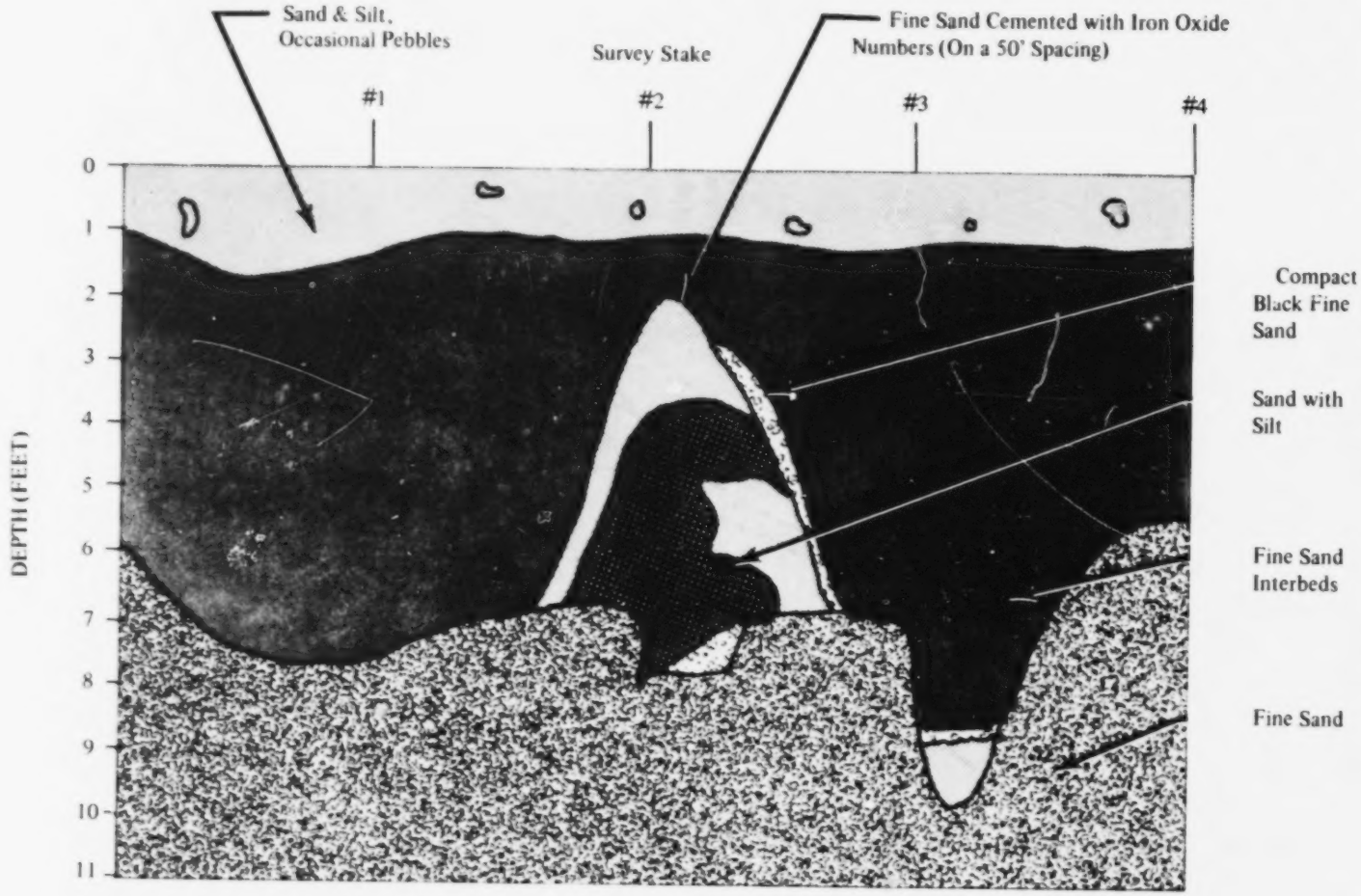


Figure 53. Geological Cross Section in Glacial Delta (See Figure 50)

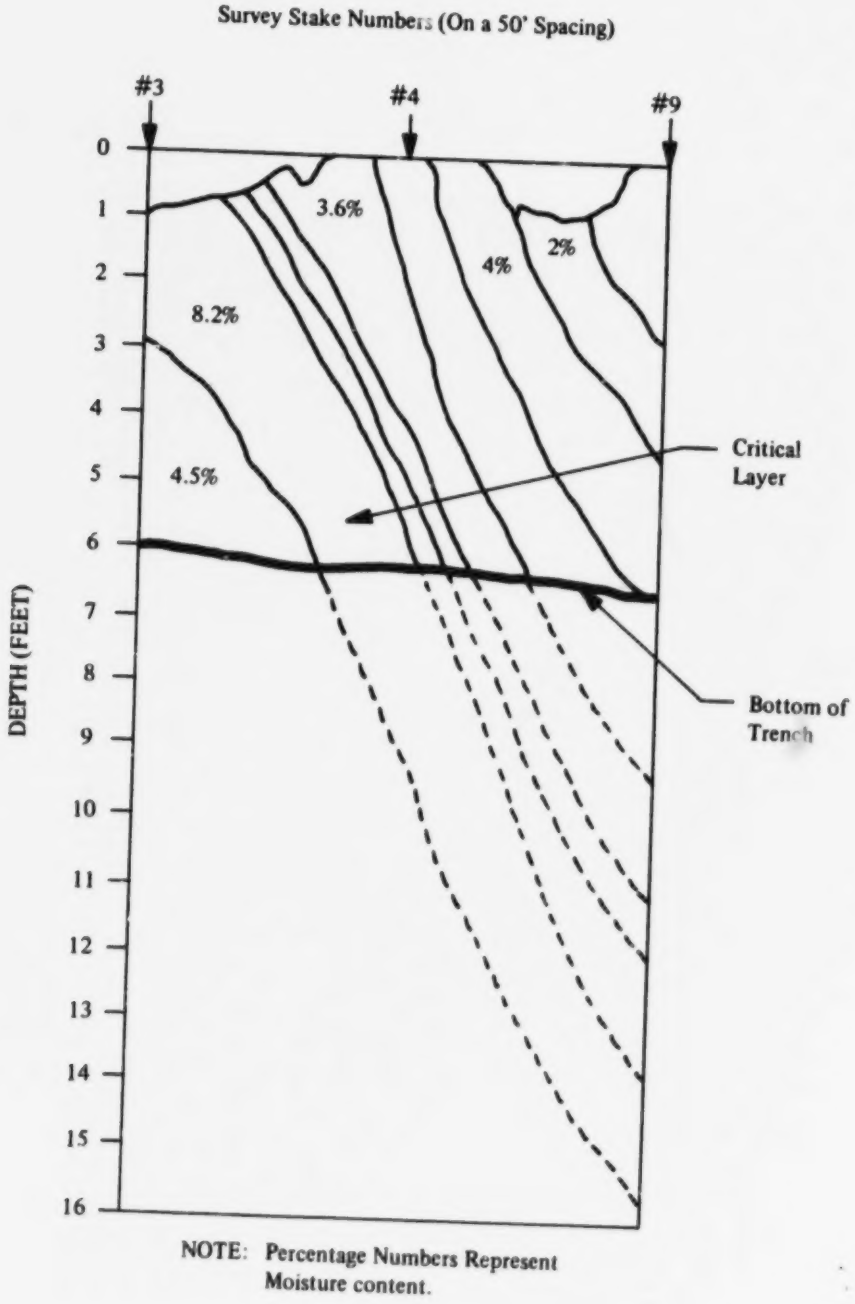


Figure 54. Geological Cross Section of Figure 51. Interbedded Sand and Silt

A second deltaic deposit was studied in the Northfield, Massachusetts area of the Connecticut River Valley. These deltaic deposits were laid down in a pre-glacial lake that occupied the valley in early post-glacial times. The deposits consist of pebble and cobble gravel overlying pebbly sand. Figure 55 is an ESP profile from a scan in this area. Sample 0016-38 in **Table 1** is sand from this site. The depth scale and resolution are the same as for the Groveland, Mass., site. The topset and foreset beds are distinct and lensing is easily picked out. Maximum depth of penetration is 25-feet. A photograph of a cut bank parallel to the scan line is shown in Figure 56.

Glacial Till

Till is defined as non-sorted, non-stratified sediment carried or deposited by a glacier. Tills are encountered constantly in glaciated regions and are therefore worthy of investigation. They are mixtures of material of all grain sizes from clay to cobbles and boulders. As percentages of each can differ greatly from place to place, it is not possible to categorize the system's operational characteristics in "till". Four sites selected for investigation by the ESP System contained till as the major unlithified material. **Table 2** lists the locations of these sites and compares the composition of the materials. Note the differences and similarities in these till samples. For example, the till from Methuen and Billerica are very similar, each having a high clay content. The till from Burlington and Groveland are also quite similar and these have low clay conten'. Note the differences in the electrical properties of the two basic types of till. The important difference is the attenuation characteristics. The sample having high clay content has an attenuation of 15.8 db, whereas the sample having the low clay content had an attenuation of 2.8 db. It would be expected that depth of penetration in the Methuen and Billerica sites would be limited. This is borne out in the samples of data from these two sites shown in Figures 57 and 58. Conversely, good depth of penetration could be expected from the Burlington and Groveland sites. This is also borne out as is shown in samples of the data from these areas shown in Figures 59 and 60. Note the confused character of the interfaces and compare them to the very orderly interfaces from the deltaic regions (Figures 50 and 55). The data sample of glacial till in Billerica was recorded along the top of a cut bank. A silt layer varying from 2 to 4 1/2-feet deep could be seen in the bank. This layer can be seen in the data and its depth correlates well with the calibration determined in the laboratory of the material from this site (0016-15).

Clay

Two sites were selected to study the system's capabilities in clay deposits. A site in Cambridge, Massachusetts was selected which had 4- to 8-feet of artificial fill, sand and gravel, underlain by massive impermeable marine clay. The clay is from 3- to 14-feet thick and is underlain by glacial till. Figure 61 is a printout of the data from one of the survey lines taken at this site. Note that a well-defined, strong reflection is received from the top of the clay deposit. Some weak reflections are received from below this interface indicating high attenuation of the signal. The sample of the clay from this site (sample 0016-36) was tested in the laboratory. Because of the difficulty in packing the clay into the electrical test sample tube, a realistic test sample density was not achieved and the sample was tested with an inordinate quantity of air voids. For this reason the electrical characteristics shown in Table I must be considered approximate and low. It can also be seen from the data that the discrimination limit in clay is 18-inches.

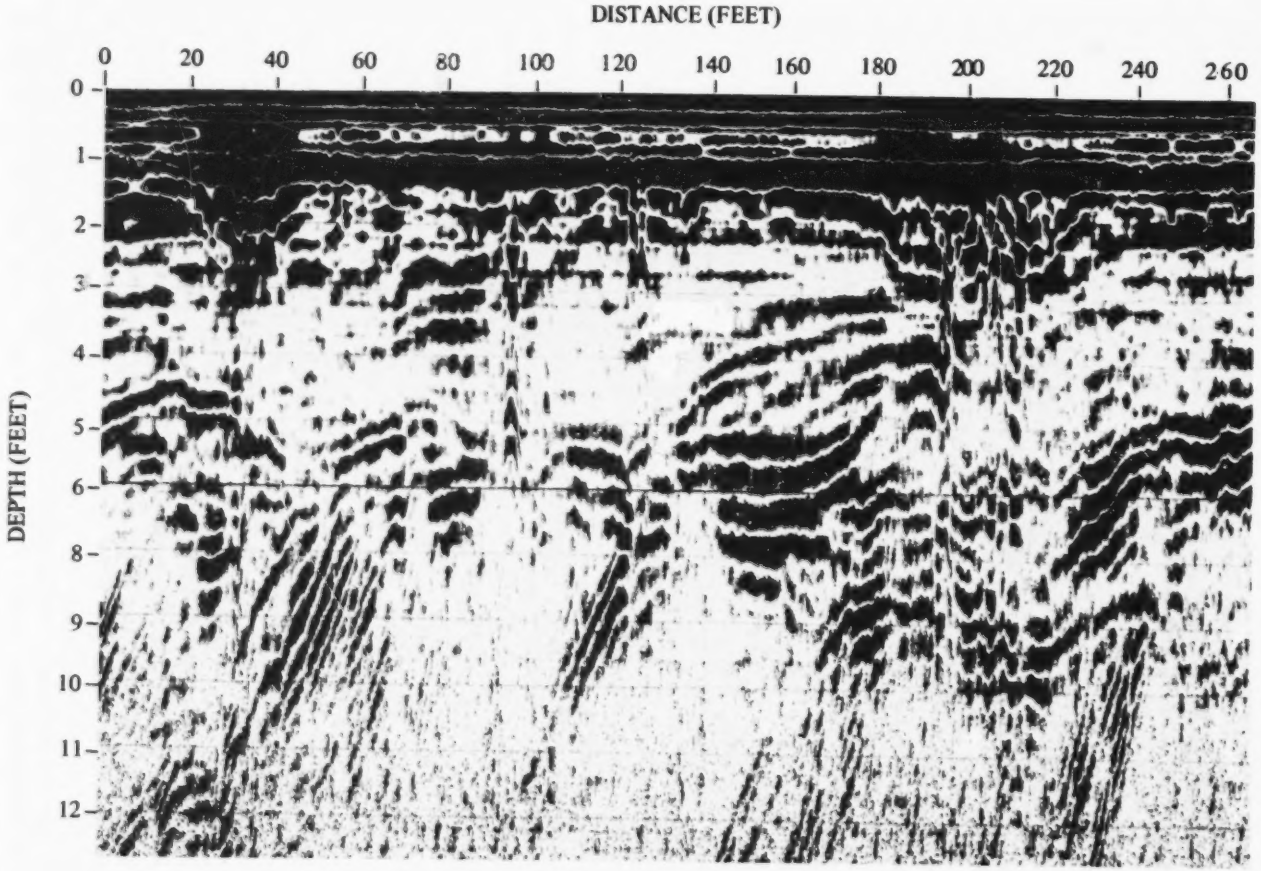


Figure 55. Data from Northfield Test Site

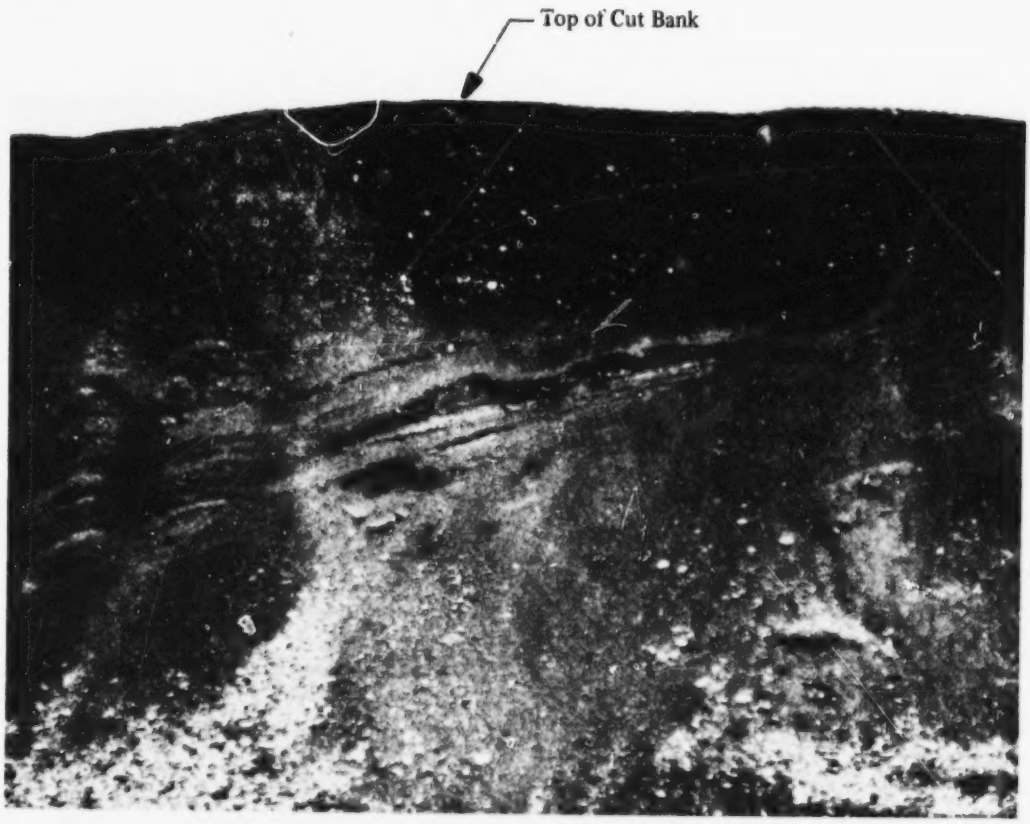


Figure 56. Cut Bank at Northfield Test Site

SAMPLE	LOCATION	SAND %	SILT %	CLAY %	MOISTURE CONTENT	DIELECTRIC CONSTANT	ATTENUATION db
0016 - 14	METHUEN, MA.	31	56	13	10	.	.
0016 - 15	BILLERICA, MA.	48	36	16	7.6	11	15.8
0016 - 23	BURLINGTON, MA.	65	33	2	7	.	.
0016 - 30	GROVELAND, MA.	68	30	2	12.3	6.9	2.8

Table 2. Comparison of Till Samples

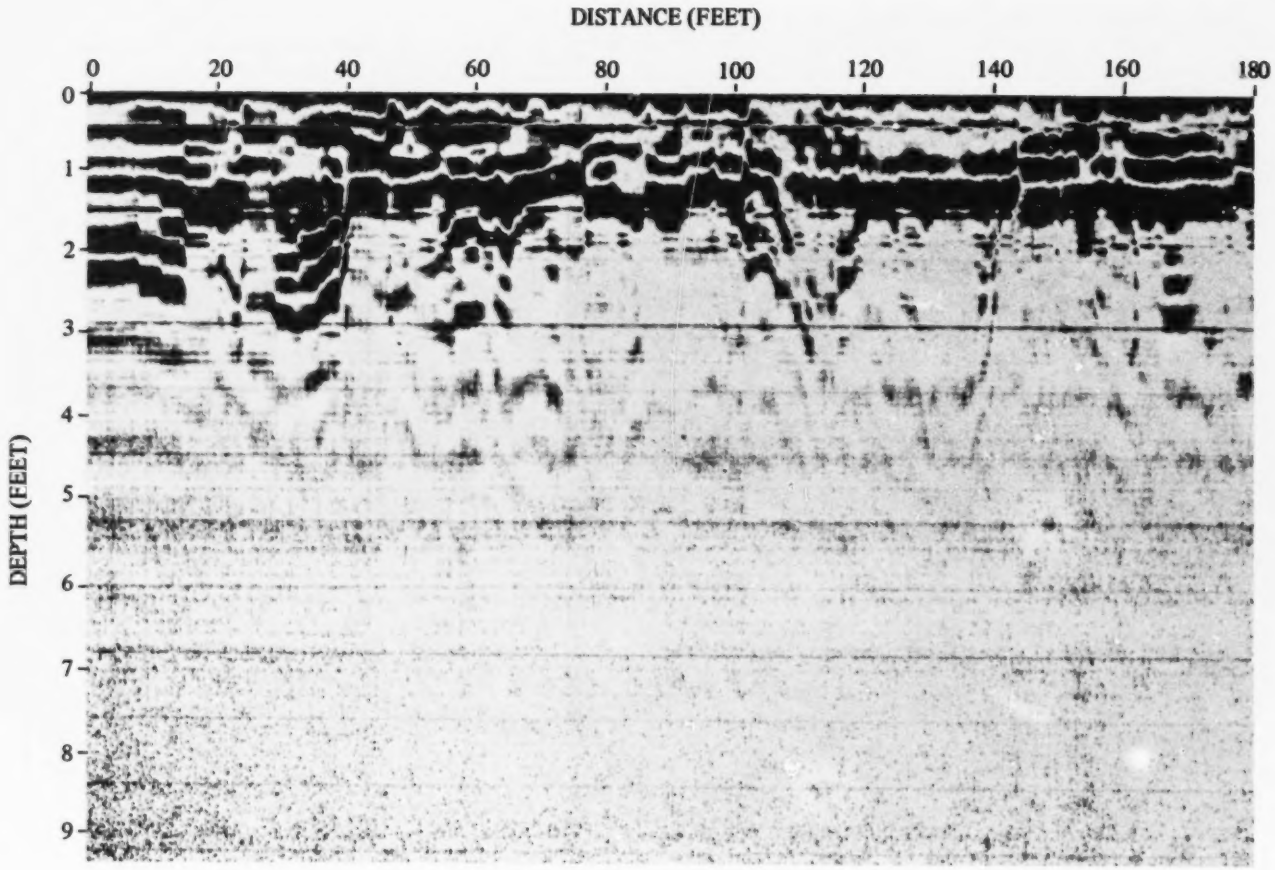


Figure 57. Data From Methuen Test Site (Till)

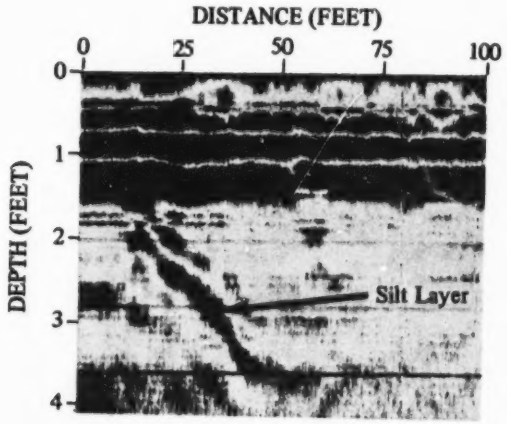


Figure 58. Data From Billerica Test Site (Till)

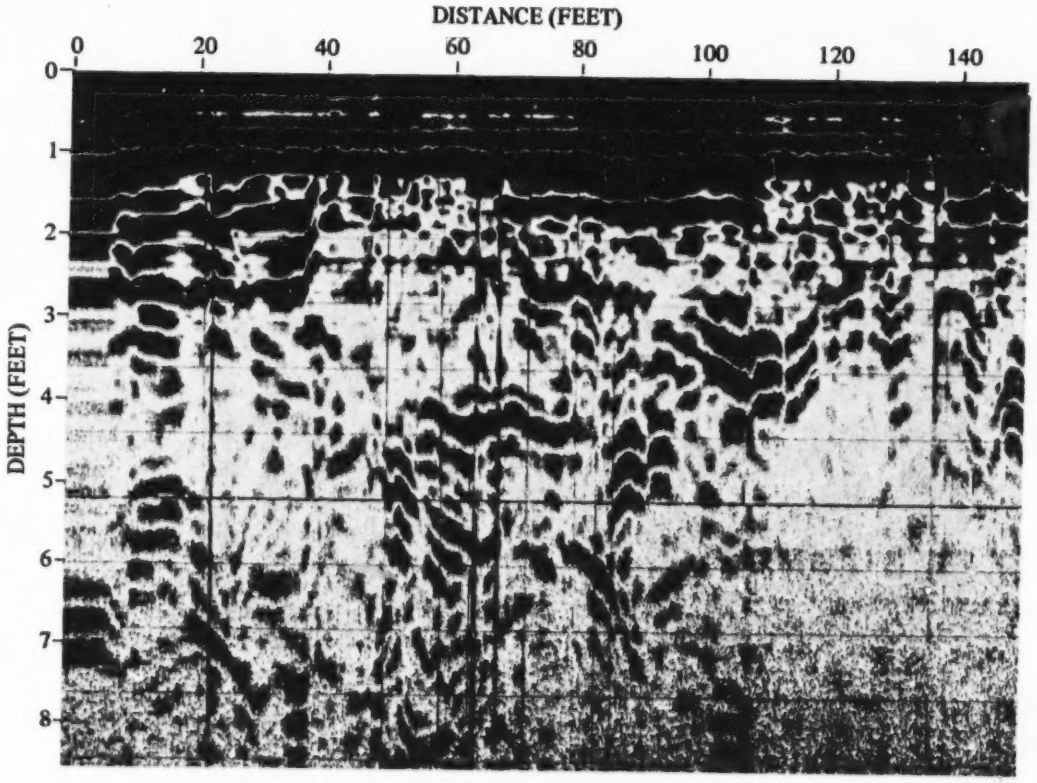


Figure 59. Data From Burlington Test Site (Till)

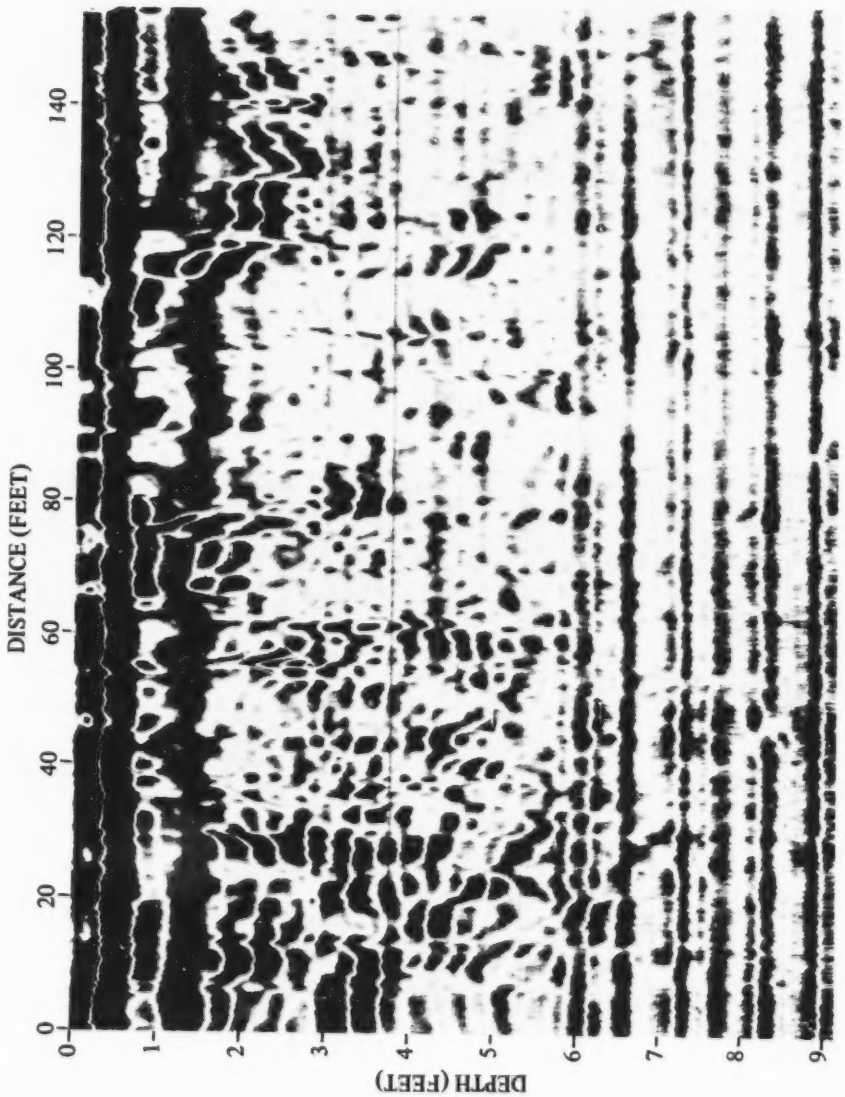


Figure 60. Data From Groveland Test Site (Till)

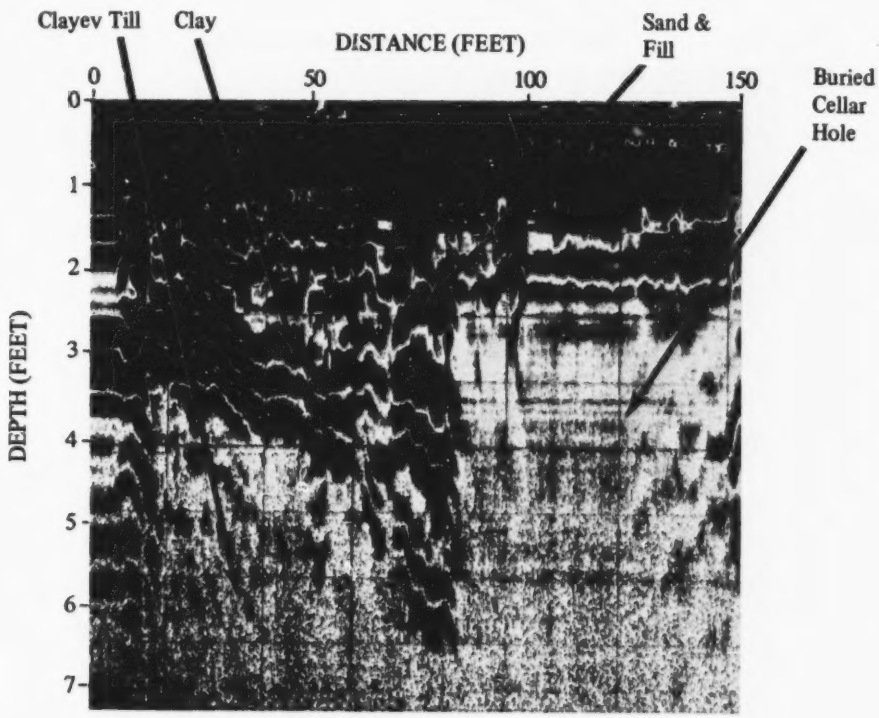


Figure 61. Cambridge Test Site (Clay)

A second site was investigated in the Northfield, Massachusetts area of the Connecticut River Valley in the same general area as that studied for deltaic deposits. Figure 62 is a data printout of a scan taken over lacustrine deposits consisting of thin, alternating beds of silt and clay.

Test probes were made at selected points along the survey path to determine the depth to the top of the clay beds. The reflection from the top of the clay beds is well defined in the data. Of particular interest in this scan is the reflection from an interface within the clay beds. This is probably an unusually thick layer of silt. The printout of this interface is another good example of signal attenuation through a lossy medium. Note that this is a lens shaped deposit, being very thin at the edges and having a maximum thickness of approximately 5 1/2-feet. Note that as the thickness of the deposit increases, the reflection of the silt layer becomes weaker until at 5 1/2-feet it is barely discernible. This indicates that the maximum depth of penetration into a varved clay deposit of this type is 5 1/2-feet. Samples of the clay deposit were tested in the laboratory but, because of the extreme difficulty in handling this material, the electric measurements were not conclusive. The electrical characteristics of this material are assumed to be similar to those of sample 0016-36.

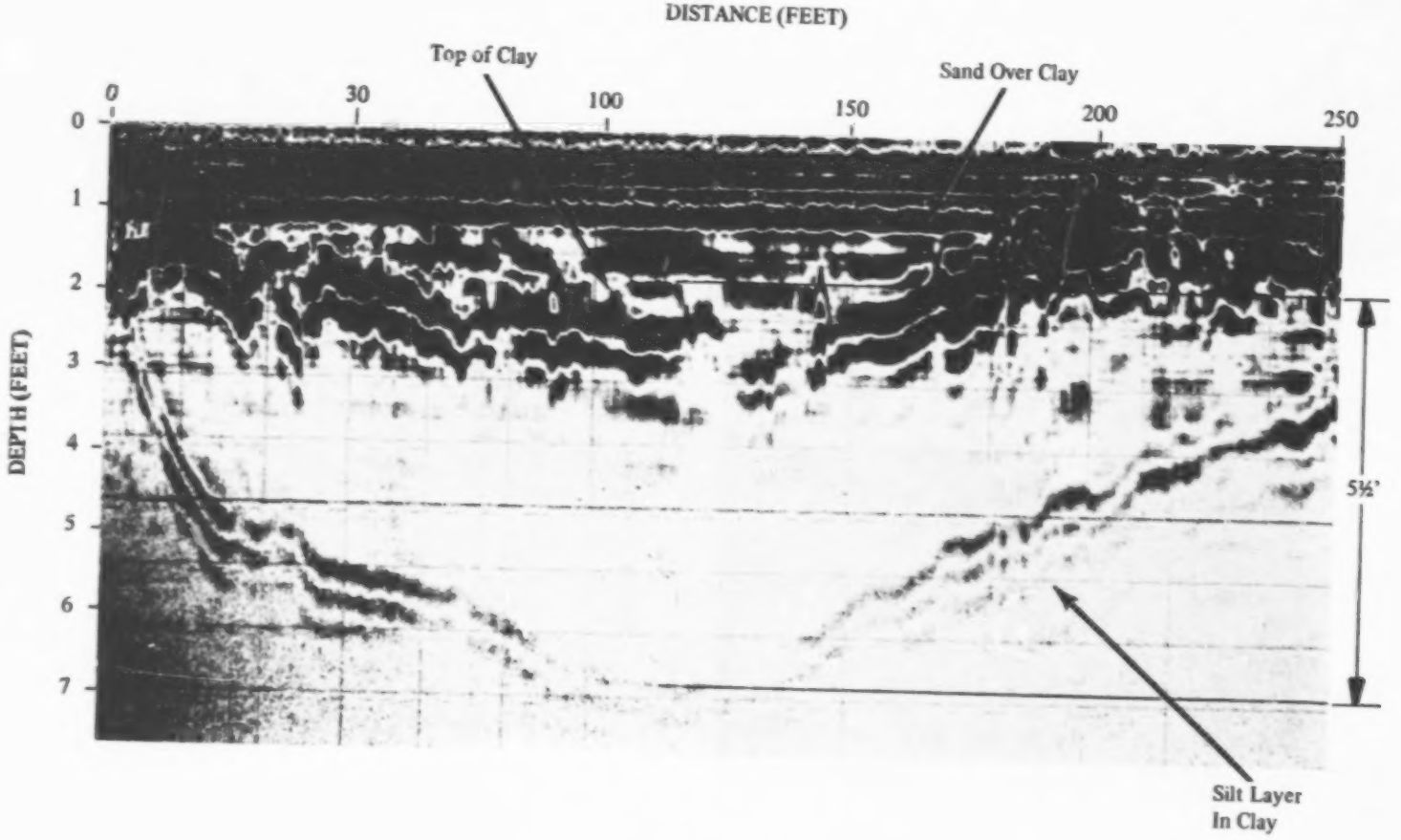


Figure 62. Data from Northfield Test Site (Clay)

As can be seen from these data and from the data collected on tills, the presence of clay in an area greatly decreases the capacities of the system, although some information can be collected. The operation of the system is dependent upon a number of variables, the most important of these being the percentage of clay in the material and the moisture content of the material. More study of the system operation in clay media is necessary.

Bedrock

The most difficult materials to evaluate are the formations of igneous and metamorphic rock. Whereas sedimentary rocks have a layered or a flat structure and therefore good reflective characteristics, the igneous and metamorphic rock have highly irregular surfaces. These irregularities scatter more energy than they reflect. This may account for the absence of reflected signal or the confused nature of the reflected signals from areas of known bedrock. The detection of bedrock from the ESP data must be done by an experienced interpreter. At present the ESP survey must be coupled with a field investigation performed by a trained geologist. After this investigation, the data from probable bedrock areas are examined for the many signatures of bedrock. Figures 63 through 66 are examples of data taken in known bedrock areas. These data were taken over paths where bedrock shows in a parallel sidecut, or across the path above outcrops, or in areas where bedrock is known to be and later verified by borings. Figure 63 is a sample of data that was taken across the top of a rock surface and away from the rock. Where the rock is at the surface there is an absence of well-defined reflections. As the rock gets deeper the sand interfaces lens in with the rock surface. These help to identify the location of the rock surface. Figure 64 is a sample of data taken along a path parallel to a cut which showed bedrock. The bedrock has a less definite interface reflection and is more defined by the lack of a signal. Figure 65 is another sample of bedrock close to the surface. However, in this sample notice the more definite reflections from the rock surface. Also note the characteristic lack of signal below the rock surface. Figure 66 is another example of data taken along a path where bedrock was close to the surface. Probes were made through the sand overburden to the top of the bedrock. Note the confused type of reflection received from the bedrock and also note the strong reflections received from the bedded sand overburden.

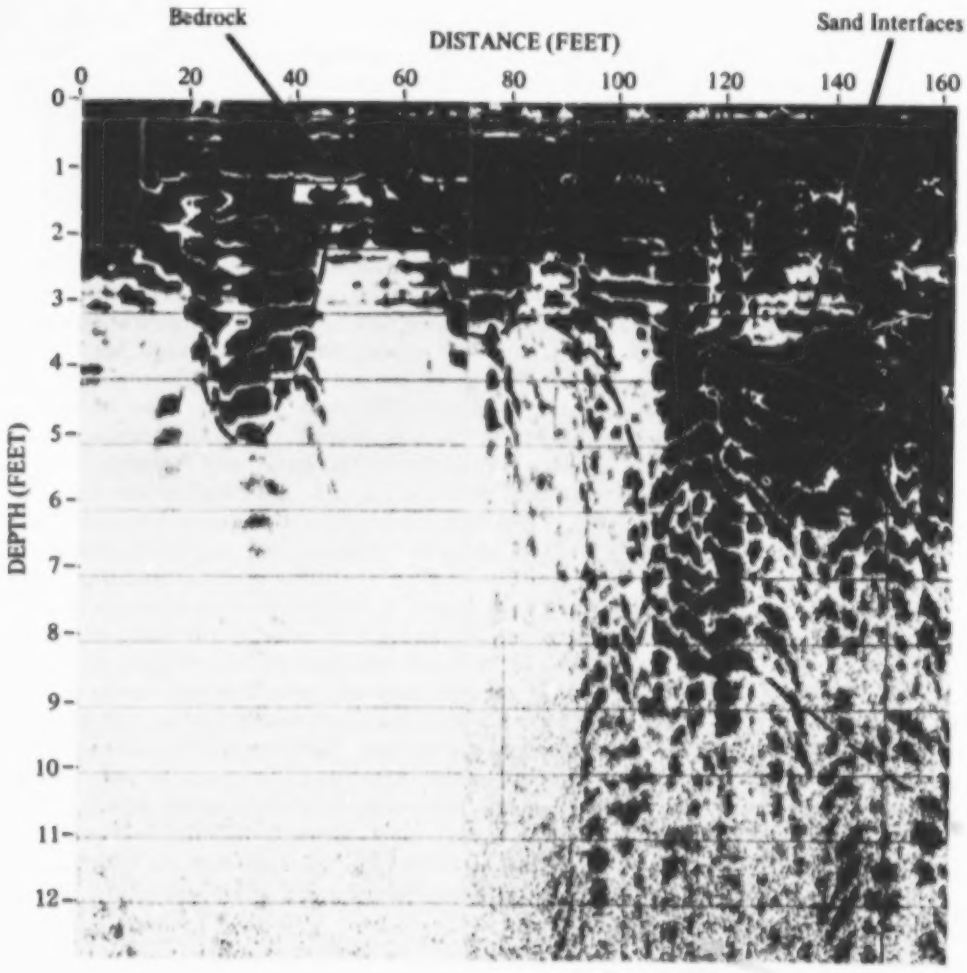


Figure 63. Route 3 and 62 Test Site (Bedrock)

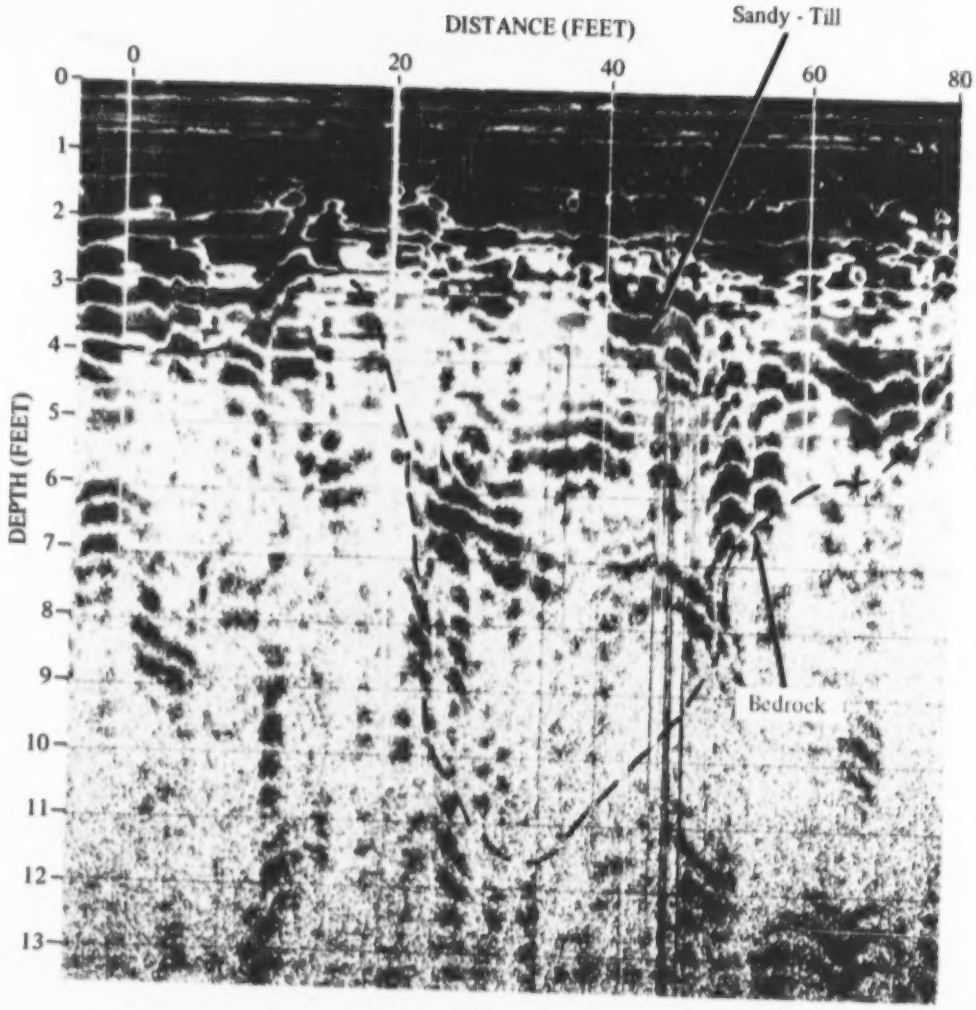


Figure 64. End of Route 3 Test Site (Bedrock)

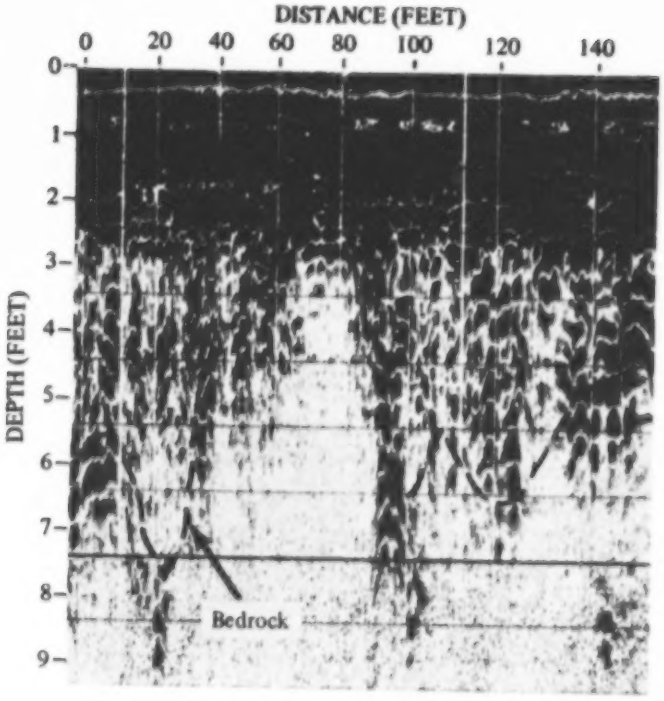


Figure 65. Burlington Test Site (Bedrock)

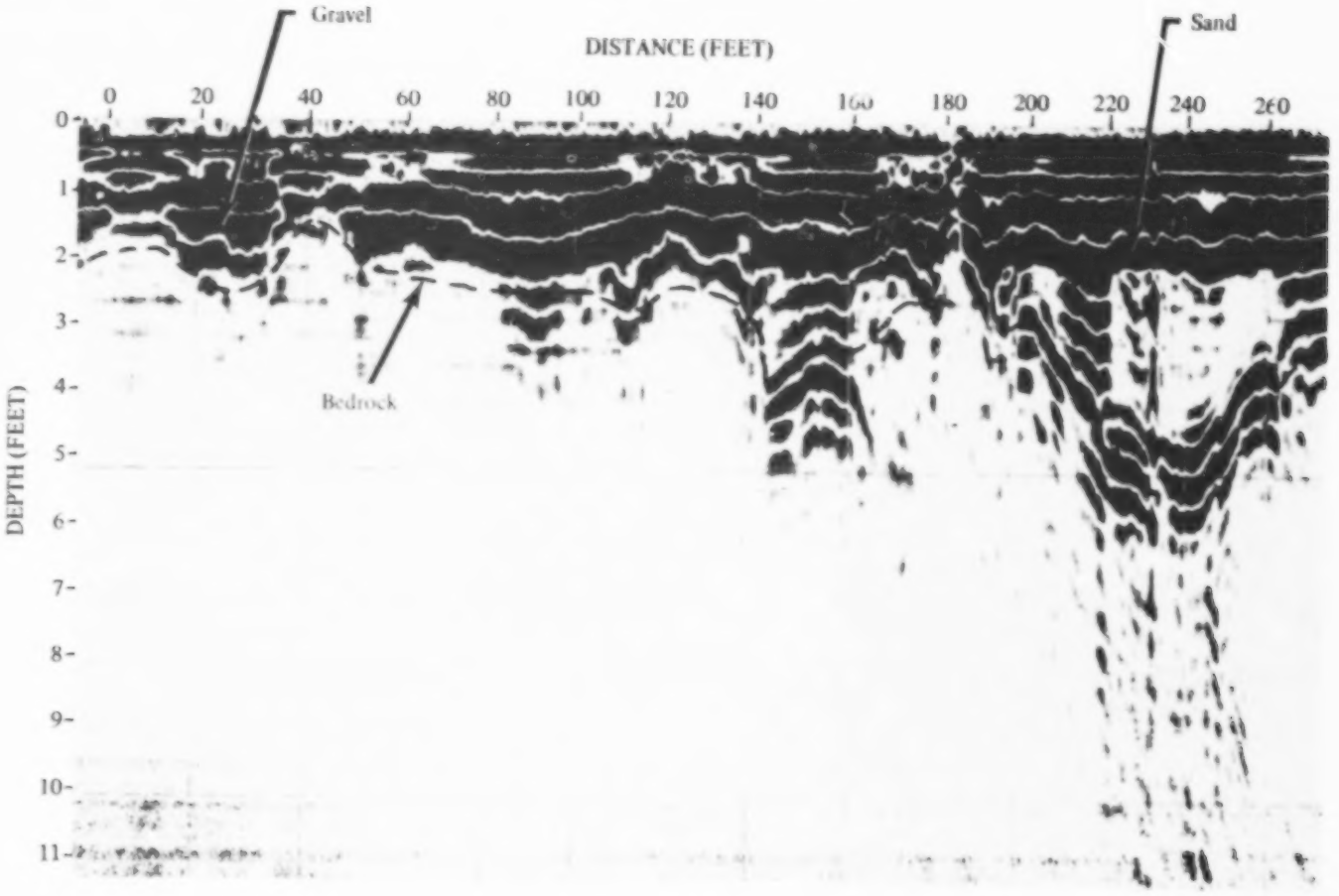


Figure 66. Northfield Test Site (Bedrock)

SECTION IX

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SECTION X

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SECTION XI

GLOSSARY

Angle of Incidence; the angle between the normal to the surface at the point of incidence and the line of propagation approaching the surface.

Attenuation; the reduction of the amplitude of an electrical signal.

Characteristic Impedance; the ratio of voltage to current that depends only on parameters of the transmission line.

Conductivity; a measure of the ability of a material to conduct an electric charge, the reciprocal of resistivity.

Dielectric Constant; the permittivity of a material.

Electromagnetic Wave; a wave propagating as a periodic disturbance of the electromagnetic field.

Impedance; symbol Z; a measure of the total opposition to current flow in an alternating current circuit, equal to the ratio of the root mean square electromotive force in the circuit to the root mean square current produced by it, and is usually represented in complex notation as, R + jX, where R is the ohmic resistance and X is the reactance.

Permittivity; the ratio of electric flux density produced by an electric field in a medium, to that produced in a vacuum by the same field. Also called "relative permittivity" or dielectric constant.

Pulse; an abrupt change in voltage, either positive or negative with respect to a reference, that conveys information. This change is characterized by a rise and decay of a finite duration.

Pulse Width; the time in seconds of the duration of the pulse measured between the half-power points of the pulse.

Radar; a mehtod of detecting distant objects and determining their position, velocity, or other characteristics by analysis of very high frequency radio waves reflected from their surface. RA(DIO) D(ETECTING) A(ND) R(ANGING).

Reflectivity; the ratio of the reflected electric field intensity at the interface or target divided by the incident electric field intensity.

Signature Test; a test in which reflected power from the interface or target is measured as the antenna is moved through a range of incidence angles.

Step Function; a mathematical function that rises in zero time to unity and remains at unity for all time (a normalized D.C. voltage, for example).

Time Domain Reflectometry; a method of measuring reflections in the time domain from discontinuities occurring on a transmission line.

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